NASA/TM–2011-217050

Entry, Descent and Landing Systems Analysis: Exploration Feed Forward Internal Peer Review Slide Package

Edited by

Alicia M. Dwyer Cianciolo
Langley Research Center, Hampton, Virginia

February 2011

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National Aeronautics and
Space Administration

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Hampton, Virginia 23681-2199

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Table of Contents

Note that all numeric values correspond to the PDF page number and are bookmarked.

Abstract

NASA senior management commissioned the Entry, Descent and Landing Systems Analysis (EDL-SA) Study in 2008 to identify and roadmap the Entry, Descent and Landing (EDL) technology investments that the agency needed to successfully land large payloads at Mars for both robotic and human-scale missions. Year 1 of the study focused on technologies required for Exploration-class missions to land payloads of 10 to 50 mt. Inflatable decelerators, rigid aeroshell and supersonic retro-propulsion emerged as the top candidate technologies. In Year 2 of the study, low TRL technologies identified in Year 1, inflatables aeroshells and supersonic retropropulsion, were combined to create a demonstration precursor robotic mission. This part of the EDL-SA Year 2 effort, called Exploration Feed Forward (EFF), took much of the systems analysis simulation and component model development from Year 1 to the next level of detail.

A main objective of the study was to determine the maximum payload mass capability of a Delta IV-H launch vehicle (launch mass of 7.2 mt) for the 2024 Mars opportunity. The simulation results, using the latest component mass models, indicated that a direct entry system could deliver approximately 3.5 mt to 0 km above the MOLA areoid. A second objective was to characterize the performance required of the supersonic retro-propulsion system. The study, which assumed four engines with a specific impulse of 338s and a system thrust to weight of 3.7 Mars g's, yielded descent engine initiation between Mach 1.4 and 1.8 at an altitude between 3 and 8 km. A third major objective was to use the high fidelity entry simulation to characterize an ALHAT like sensor suite for Mars. Initial performance range results were obtained for terrain relative navigation, hazard detection and avoidance, velocimeter and altimeter sensor systems.

This document includes the slides presented at the EDL-SA EFF Internal Peer Review held at Johnson Space Center December 1 and 2, 2010 at the conclusion of the study.

Supporting Documentation

This document is intended to complement other EDL-SA documents, including the Year 1 Summary document "Entry, Descent and Landing Systems Analysis Study: Phase 1 Report" NASA/TM-2010-216720, the Year 2 EFF summary report, "Entry, Descent and Landing Systems Analysis Study: Phase 2 Report on Exploration Feed Forward Systems," and the "Entry, Descent and Landing Systems Analysis (EDL-SA) for High Mass Exploration and Science Mars Mission Systems: Final Report," EDLSA-004, December 2010.

1.0 EDL Systems Analysis (EDL-SA) Exploration Feed Forward (EFF) Internal Peer Review (IPR) Introduction

Ron Sostaric

Welcome

Thank you all for coming and participating in this review.

Team Members

EDL-SA

EFF Team

- Jim Arnold
- Alicia Cianciolo
- Jody Davis
- Walt Engelund
- Eduardo García Llama
- David Kinney
- Shawn Kirzan
- Kathy McGuire
- Jeff Murch
- Aaron Olds
- Dick Powell
- Eric Queen
- Jamshid Samareh
- Jeremy Shidner
- Ron Sostaric
- David Way
- Carlie Zumwalt
- Tom Zang

Panel

- Anthony Calomino
- Chuck Campbell
- Chris Cerimele
- Karl Edquist
- Chirold Epp
- Mark Hammerschmidt
- Steve Hughes
- Mark Rezin
- Mike Wright

Successful inter-center cooperation between EFF team members from LaRC, JSC, and ARC

Charge to the Board

EDL-SA

- Please assess the following:
  - appropriateness of component models
  - appropriateness of end-to-end simulation models
  - credibility of simulation results
  - completeness of technologies considered
  - reasonableness of evaluation/selection criteria
  - reasonableness of technology recommendations
- We also request recommendations for future work
  - improvements that would increase the credibility of the EFF study
  - issues that should be addressed in future studies
- As the project has a firm end date of 31 Dec per explicit NTEC direction, no additional work is expected to be completed. Board comments will be compiled and assembled in a document which will be provided to our HQ stakeholders and made available for future studies
- Please submit comments using comment form (either electronically or hard copy) to Ron Sostaric or Alicia Cianciolo

Comment Forms

- Please use form for written comments
- Request your assessment of impact or priority of the comment (low, med, high, N/A)
  - High – affects credibility of results
  - Low – nice to have
  - N/A if not applicable
- Prefer to have comments electronically over hard copy, but prompt return is the highest priority so feel free to use whatever method is most convenient to you

Project Overview

Objectives of EDL-SA Study

EDL-SA

- **Overall Objective:**
  - **Develop a strategy and plan for NASA to be able to successfully land large payloads at Mars for both robotic and human scale missions**
- **Year-by-Year Foci**
  - **Identify the broad areas requiring technology development for Exploration-class missions (Year 1)**
  - **Identify the broad areas requiring technology development for large-robotic-class missions (Year 2)**
  - ~~**Develop detailed, costed, integrated (cross-cutting) technology development plans to TRL = 6 (Year 3)**~~

EDL-SA FY 11 Options Presented to NTEC

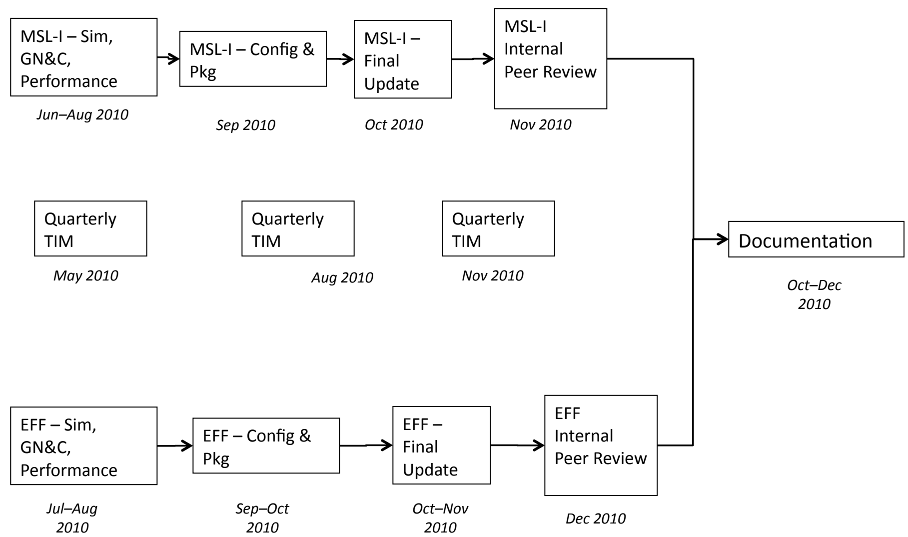
EDL-SA

Product	Option 0	Option A*	Option B
	End 9/30/10	End 12/31/10	End 3/31/11
Slide Package Documentation of Incomplete Technical Work	✔		
Complete All Planned Technical Work		✔	✔
Summary (Architectural-level) Written Documentation		✔	✔
Complete Additional MSL-I and EFF/ALHAT Work			✔
Conduct External Peer Review & Respond to RFAs			✔
Detailed Written Report & Conference Papers			✔

Option A Selected by NTEC in July 2010

EDL-SA Close-out Schedule

EDL-SA



EDL-SA Status

(*vis a vis* the original plan)

EDL-SA

Year 1

- **Define DRM's**
- **Define Study Assumptions**
- **Update needed tools**
- **Assess Exploration Class Mission Technologies**
  - Define candidate technologies and architectures
  - Develop Trade Trees
  - Define Exploration Class parameters - aero, OML, mass props., packaging, etc.
  - Perform architecture assessment
  - Finalize results
  - Plan viability testing
- **Early assessment of higher TRL Robotic Class Mission Technologies**
- **Define initial development pathways for Exploration Technologies**
- **Reporting**
  - Peer reviews
  - Sponsor reviews
  - Final results reviews
  - Documentation

Year 2

- **Update DRM's**
- **Perform viability testing for Exploration Class Mission Technologies**
- **Assess Robotic Class Mission Technologies**
  - Define candidate technologies and architectures
  - Develop Trade Trees
  - Define Robotic Class parameters - aero, OML, mass props., packaging, etc.
  - Perform architecture assessment
  - Finalize results
  - ~~Plan viability testing~~
  - ~~Initiate viability testing~~
- ~~**Define initial technology development pathway**~~
- **Reporting**
  - (Internal, ~~External~~) Peer reviews
  - Sponsor reviews
  - Final results reviews
  - Documentation
- ~~**Complete planning for cost and development schedule assessment**~~

~~***Year 3***~~

- ~~**Complete viability testing for Robotic Class Mission Technologies**~~
- ~~**Complete detailed Exploration Class Mission Technologies Development Pathways**~~
  - ~~Development schedule~~
  - ~~Define precursors~~
  - ~~Costs~~
  - ~~Complete detailed~~
- ~~**Robotic Class Mission Technologies Development Pathways**~~
  - ~~Development schedule~~
  - ~~Define precursors~~
  - ~~Costs~~
- ~~**Reporting**~~
  - ~~Peer reviews~~
  - ~~Sponsor reviews~~
  - ~~Final results reviews~~
  - ~~Documentation~~

Green: completed by August 2010
Orange: complete by December 2010

BACKUP

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EFF Technology Infusion

- EFF briefed the OCT EDL Roadmap Team (Aug. 25)
  - All EFF technologies are covered (at a high level) in the draft OCT EDL Roadmap
- EFF briefing to OCT project managers is planned
- Key ARMD & ESMD technology element managers are members of the EFF Internal Peer Review Panel (chart #10)
- EFF has interacted heavily with ALHAT project
- EFF will provide relevant KPP's to ESMD's EDL TDP and ARMD/OCT's HIAD project

Technology Investment Areas

EDL-SA

Technology Area	TDP Content
Rigid Decelerators	Tools & processes for generating aero/aerothermal databases & mass models; rigid, dual heat-pulse capable TPS; structures; rigid decelerator (aeroshells and deployables) shapes for aerodynamic performance and controllability; vehicle designs
Flexible Decelerators	Tools & processes for generating aero/aerothermal databases & mass models for flexible entry/aerocapture vehicles; flexible materials, flexible decelerator shapes for aerodynamic performance, structural strength and controllability; vehicle designs
Precision Landing	Sensors, navigation and controls and their integration for precision landings with hazard avoidance in atmospheres
Supersonic Retro-Propulsion	Aero-propulsion interaction propulsion for supersonic deceleration—tools, controls, and configurations. Works for high supersonic initiation through touchdown.
All-propulsive Design	System studies of open issues for hypersonic phase and staging
Aerocapture Development	Requirements for an Aerocapture Technology Validation Flight Test
Supersonic Retro-Propulsion Flight Test Program	Flight demonstration (TRL=6) of controllability from initiation to simulated touchdown of supersonic retro-propulsion descent system.
Deployable Decelerator Flight Test Program	Flight demonstration (TRL=6), including controllability of Deployable, Inflatable Aerodynamic Decelerator
Aerocapture Flight Test	Flight demonstration (TRL=6–7) in upper Earth atmosphere
Parachute Flight Test Program	Flight testing of a supersonic Ringsail parachute, including reefing and deployment of a large (>21.5m diameter) parachute at Mach >2.0

2.0 EDL-SA Exploration Feed Forward Overview and Objectives

Alicia Cianciolo

Mars Design Reference Architecture (DRA5) 2008

- **Objective: To determine minimum required technologies to develop credible AEDL concept that would safely land 40 MT**
- **Baseline Mission: Rigid body (Ellipsled) concept (highest TRL of the candidates) and Supersonic Retropropulsion**
  - **Eliminated parachutes (too large to be credible)**
  - **Eliminated inflatables, rigid deployables, etc. (too low TRL, insufficient models)**
  - **Selected dual-pulse TPS**
  - **Selected Supersonic Retro Propulsion (note low TRL because of controllability concerns, but deemed best credible solution)**
  - **Trajectory simulation included low fidelity models**
  - **Resulted in 110 mt arrival mass**

EDL-SA: Exploration Class
2009

EDL-SA

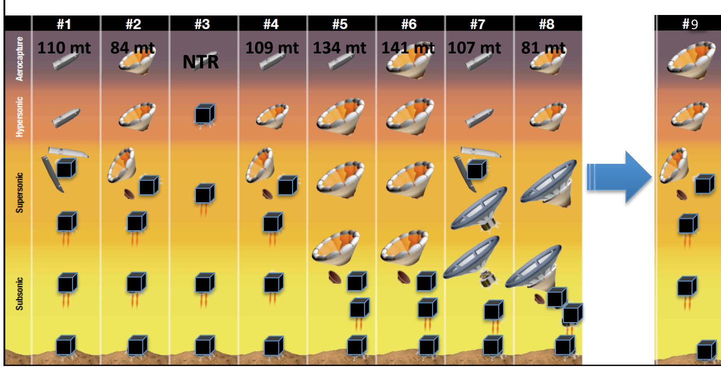
Open the design space to include additional low TRL solutions

- Performed more detailed analysis of the DRA 5 solution
- Identified potential alternate technology paths – try to have multiple paths through the technology space
- Used data from previous studies as a starting point (e.g. used MIAS study (HIAD with ablator TPS) to develop alternative to rigid body)
- Decided to investigate SIAD with subsonic retropropulsion as alternative to supersonic retropropulsion
- Recognized that many potential credible solutions were not examined (e.g. rigid deployables)

EDL-SA: Exploration Feed Forward
Evolution

EDL-SA

- EDL-SA Exploration Class Study considered combinations of technologies required to land humans on Mars with
  - Undefined 40 mt Payload
  - HIAD ablator TPS
  - Bank angle control
- After Exploration Class External Peer Review
  - Suggested to consider insulator TPS for Entry and Aerocapture HIADS to compare the mass saving over ablator TPS
  - Suggested that that bank control may not be feasible for large HIADS, so considered CG control



EDL-SA: Exploration Class, cont.
2009

EDL-SA

- **Conclusions of Exploration Class Analysis**
  - DRA 5 concept still viable
    - Limited testing of dual pulse TPS showed promising results
  - Replacing SRP with SIAD and subsonic retropropulsion not a good trade
    - No credible alternative to SRP identified
  - HIAD's offered potential for large arrival mass reductions
  - Rigid aeroshells, SRPs and HIADs with ablator TPS were recommended for technology development
- **Transition to Exploration Feed Forward (EFF)**
  - Testing of HIAD insulator TPS material showed promising results
  - Controllability of concept with HIAD remained major concern
  - Updated packaging analysis of DRA 5 aeroshell configuration showed that internal volume was oversized – vehicle could be reduced in size and thus arrival mass should be reduced
  - Recognized that rigid deployables should be added to candidate technology list
  - Decision to split EDL-SA 50/50 with MSL-I limited resources to a single concept (with trades) to carry forward – selected HIAD for aerocapture and EDL

EFF Objectives

EDL-SA

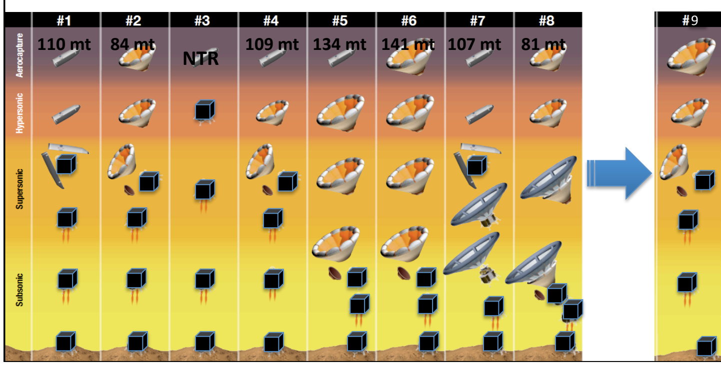
To determine if technologies identified in Exploration Class analysis can be combined in a precursor mission to successfully land a payload of $\geq$2.5 mt

1. **Determine the maximum payload delivery capability of a Delta IV-H**
2. **Determine required performance of supersonic retropropulsion**
3. **Increase the level of fidelity of all models**
4. **Determine optimal materials, L/D and HIAD size for aerocapture and entry**
5. **Determine if cg control provides benefits over bank control**
6. **Determine sensor performance for an ALHAT system at Mars**

EFF Evolution

EDL-SA

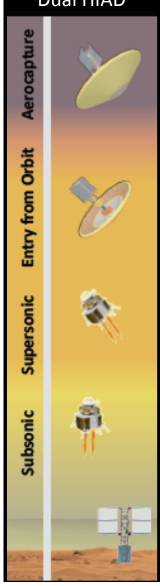
- Extended Arch 9 to assess the next level of design detail using
  - Arrival mass limited to capability of Delta IV-Heavy
  - 2 mt specified Payload (Nuclear Power Plant)
  - Separate HIADS for Aerocapture and Entry
  - HIAD Insulator TPS
  - HIAD controller options - CG, Bank and Combination
  - ALHAT sensor models
  - Supersonic Retro-propulsion (switched from LOX to Hydrazine for Year 2)



Optimal Design Selection Process

EDL-SA

Feed Forward
Dual HIAD



1. Select a Controller 2 HIAD Design: 6DOF Aerocapture Simulation Only
   Perform Controllability Assessment

Design	NOM	A	B
AC TPS	Insulator	Insulator	Insulator
Entry TPS	Insulator	Insulator	Insulator
Ctrl Method	CG	Bank	Combo

2. Select optimal HIAD TPS Design: 6DOF Aerocapture Sim/3DOF Entry

Design	NOM/A/B	C
AC TPS	Insulator	Ablator
Entry TPS	Insulator	Insulator
Ctrl Method	From Trade 1	From Trade 1

Selection Consideration:
Potential for reduced development costs and lower mass vs. packaging and controllability

3. Select 1 or 2 HIAD Design: 6DOF Aerocapture /6DOF Entry
   Perform ALHAT Assessment

Design	NOM/A/B/C	D
AC TPS	From Trade 2	From Trade 2
Entry TPS	Insulator	
Ctrl Method	From Trade 1	From Trade 1

Selection Consideration:
- Meets packaging constraints
- Provides maximum landed payload
- Stable Inertias in 6DOF
- 6DOF Simulation closes

Actual Process

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1. ALHAT sensor assessment
   - Not able to use optimized mass inertias in 6DOF entry simulation so used representative set from a September version mass model
   - Considered 6 DOF AC and Entry and 3 DOF terminal descent trajectories
   - Time limitations forced us to use prototype of ALHAT NAV filter for Mars
2. Mass Modeling Assessment
   - Four mission configurations: Dual HIAD, Single HIAD, Direct entry (7.2 & 5.8 km/s)
   - Nominal and few sensitivity studies
   - Two TPS materials: Insulator (IRVE) & Ablator (Ames)
   - Redesign Terminal Descent Engines
3. HIAD Controllability Assessment
   - Used inertias from September mass model
   - Time limitation prevented the assessment of the combo controller
   - CG controller was feasible in 3 DOF but time limitations did not yield valid results in 6DOF with EFF configuration
   - Therefore EFF considered only 6DOF bank control assessment

EFF Technology Recommendations

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- Continue evaluation of ALHAT sensors adapted to Mars
- Continue development supersonic retropropulsion
- Include rigid body precursor configuration
- Continue to mature HIADS
- Include rigid deployables in design space
- Perform detailed evaluation of transitions
- Invest in advancements in flight instrumentation

EFF Products

EDL-SA

- Answers to the 6 issues on Slide 6
- Refinement of the Technology Investment Recommendations from Year 1
- A precursor mission configuration that, under current assumptions, is capable of landing a ~3 mt payload using a Delta IV-H
- Alternative precursor mission configurations suggestions for future study
- Documentation
  - ~25-page, high-level summary published as a NASA TM
  - IPR slide presentations available to NASA Civil Servants
  - Programmatic summary for HQ funders & stakeholders
  - IPR Reviewer comments for HQ funders & stakeholders
- ***Detailed simulation capability (tools & people) for supporting future systems analysis studies—not a promised deliverable but a valuable by-product***

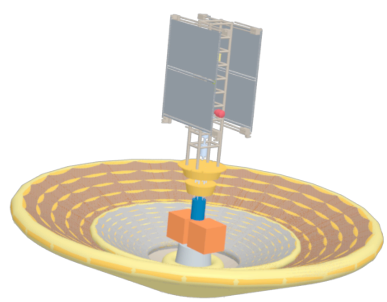
3.0 EDL-SA Exploration Feed Forward Design Reference Mission, Ground Rules and Assumptions and Evaluation Criteria

Alicia Cianciolo

EFF Design Reference Mission

Feed Forward
Dual HIAD

- **Vehicle: Delta IV-H, 5 m shroud diameter**
- **Launch C3: 15 km^2/s^2**
- **Arrival Velocity: 7.3 km/s**
- **Launch Mass: 7.2 mt**
- **65 deg sphere cone HIAD shape**
- **Dual HIAD design**
  - **Aerocapture with a 14 m HIAD into a 500 km orbit**
  - **Enter Mars at 3.35 km/s with separate 8 m HIAD**
- **Using center of gravity control for entry**
- **Initiating descent engines supersonically (M<2)**
- **Landing at an equatorial site 0 km above the MOLA areoid within 100 m with $\leq$ 1 m/s vertical velocity**



Key Ground Rules and Assumptions

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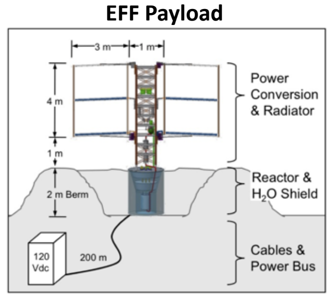
See EDL-SA Year 2 GR&A Document

- **Mass growth allowances and margins will be applied (EFF = 49.5%)**
- **Subsystem performance parameters (e.g., engine Isp, engine T/W, vehicle inert mass fraction) will be based on historical data and trends. [See Section 6.3.1]**
- **Landed altitude capability will be a minimum of 0 km above MOLA.**
- **Detailed payload will be identified for packaging: nuclear power source**
- **HIADs are assumed to be rigid bodies**
- **Structure will be sized based on loads and will include plumbing, legs, guide rails, actuators, & thruster placement**
- **System will assume sensor integration package (like MEDLI)**

EFF Payload



Evaluation Criteria

Promised EFF Results

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1. **Determine the maximum payload the Delta IV-H can deliver to 0 km MOLA at Mars**
2. **Determine the required performance of supersonic retro-propulsion system**
3. **Perform the next level of detail on packaging, mass properties, transitions, structures, propulsion, etc**
4. **Determine optimum material/TPS, L/D, and size of the HIAD for aerocapture and entry**
5. **Determine if active cg control provides benefits over the use of bank only**
6. **Determine the sensor performance ranges for an ALHAT like navigation & sensor system at Mars**

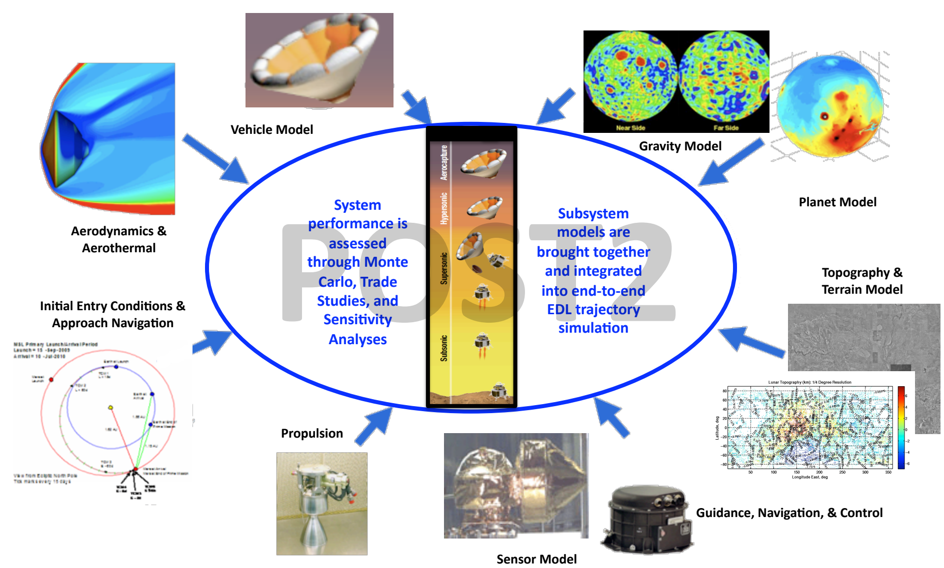
4.0 EDL-SA Feed Forward Simulation Overview

Jody L. Davis

EDL-SA Feed Forward Simulation

- Objective: To develop a unified aerocapture and entry simulation using POST2 to be used for EDL-SA Exploration Feed Forward (EFF) (also leveraged by EDL-SA MSL-I)
- EFF simulation built upon Year 1 POST2 version 1.1.8L (7/3/09) of the simulation and now includes models to support both aerocapture and EDL
  - ✓ Guidance algorithms: HYPAS, Apollo (entry & powered descent), TPC, Shape Integral & NPC
  - ✓ Control algorithms: LQR bank angle controller (aerocapture & entry) & PID controller (CG control)
  - ✓ Navigation filters: Simple propagator & ALHAT Extended Kalman filter
  - ✓ Mass Model: EFF Response Surface
  - ✓ Sensor Models: IMU, startracker, velocimeter, altimeter
  - ✓ Aerodatabases: EFF 65-deg sphere cone, Year 1 HIAD & Rigid, Genesis, Orion & MSL
  - ✓ Aerothermal Model: Ames

EDL-SA Feed Forward Simulation EDL-SA



EDL-SA Feed Forward Simulation EDL-SA

- **EFF POST2 simulation is under configuration control using ClearCase with traceability from the 1.1.8L baseline as new models are included**
  - **New simulation framework emphasizes modular components for each included model**
  - **Modularity has helped to debug many issues between models**
- **All models were evaluated using the same EFF POST2 executable to ensure consistency**
- **Configuration control has also been implemented for EFF simulation inputs**
  - **Ensures consistency between model evaluations**
  - **Developed and maintained unified POST2 input deck and Monte Carlo used by both aerocapture and EDL simulations**

EFF Single POST2 Input Deck

EDL-SA

```
c-----------------------------------------------------------------------
c Modified by J. Davis  10/18/10
c EDL-SA  6DOF Bank Angle Controlled Aerocapture or Entry Simulation
c-----------------------------------------------------------------------

c*** Choose ONE option from each type: ***

c##### DOF Type #####
c*define DOF6                // 6DOF Aerocapture or Entry
c*define DOF3                // 3DOF Aerocapture or Entry
*define PD_DOF3              // 3DOF Powered Descent (do not comment (

c##### Simulation Type #####
c*define AEROCAP
*define EDL

c#####  Guidance Type ######
c*define HYPAS
c*define TPC
c*define SHAPE
c*define APOLLO
c*define NPC_AC
c*define NPC_EDL

c##### Navigation Type ######
c*define PROPAG
c*define NAVLRC2
c*define ALHAT

c#### Manuever Type ######
*define HIAD_JETT

c#### Lift-over-Drag ######
*define LoD_0p25
c*define LoD_0p1

c#### Center Type ######
c*define JSC

*if def AEROCAP
*declare DIAM  14
*declare DIAM_JETT 4
*else
*declare DIAM  8
*endif
```

Single input deck enforces consistent model inputs

```
c **************  Event 300: Atm Exit ********************************

   event=300,critr='gcrad' ,value=3522200,mdl=8,
   npc(24)=0
*endif  //AEROCAP

// ###############!!!START EDL INPUTS HERE!!!###################
*if def EDL

   event    = 1,
   vehicle  = 1,

      // ------------------------------------
      //   Initial Conditions
      //   NAV Filter & State Initialization
      // ------------------------------------

        npc(3)   = 5,                                // Orbital Elements
        malta    = 5.00000000e+02
        maltp    = -2.19017015e+02                   // taken at EI from 3DOF Apollo Entry
        inc      = 90
        lan      = 3.33691322735950337e+02
        argp     = 4.44004987171960863e+01
        truan    = 1.80000000e+02
        time     = 0.0

      // ------------------------------------
      //   Initial Attitude
      // ------------------------------------
*if def DOF6
        iguid(1)        = -2,          / 6dof
*endif
*if def DOF3
        iguid(1)  = 0,0,1,
*endif
        iguid(12)       = 1,           / body attitude with alpha, beta, bank
        iguid(22)       = 1,           / body attitude rates with rolbd, pitbd, yawbd

        alpha           = -18.0
        beta            = 0.0
        bnkang          = 2.03635306e+01
        rolbd           = -3.35720120e-04
        pitbd           = -5.40765781e-02          / deg/s
        yawbd           = 1.63303007e-02
        alppc(1)        = 0.0,
        betpc(1)        = 0.0,
        bnkpc(1)        = 0.0,

      // ----------------------------------------
      //   FSW: Guidance, Navigation & Control
      // ----------------------------------------

        control_mode = BNKSTRATEGY      // Bank angle control

        zcgbis =0.2512          // ZoD of 0.0314 for L/D = 0.20
        ycgbis =0.0
        xcgbis =-2.5145         // XoD of 0.30 for L/D = 0.20

*if def DOF6
*include "entry_bank_lqr_lon.dat"
*include "entry_bank_lqr_lat.dat"
  bnklqr_Ts = 0.05     //  1/hz_ctrl
  controller_mode = LQRCTRL
 guid_alpha_cmdt = 'alphat' monovar velr 0 lin_inp noxt
    3.559830e+03  -1.767367e+01
    3.413960e+03  -1.760640e+01
    3.268089e+03  -1.749108e+01
    3.122218e+03  -1.750330e+01
```

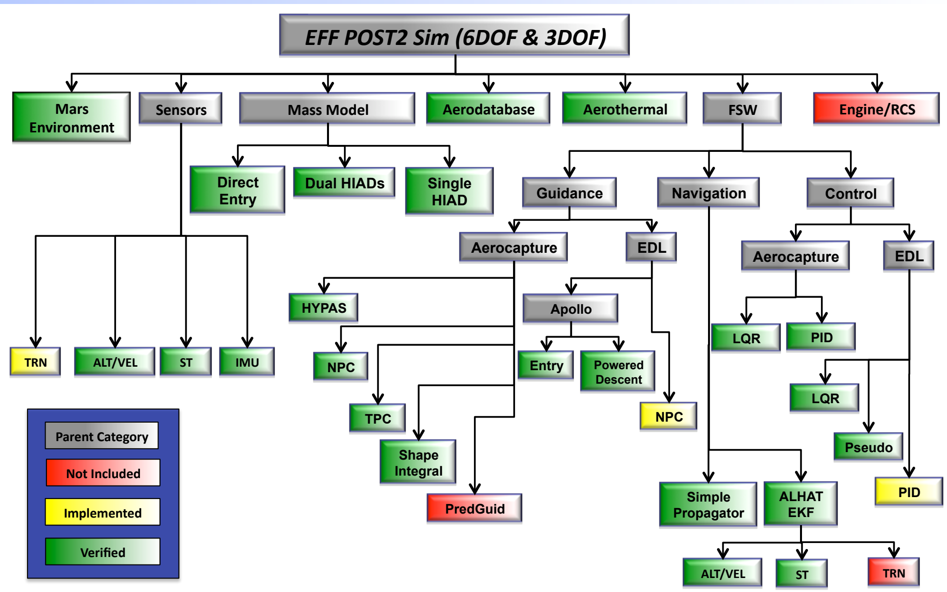
Aerocapture

EDL

Sample of POST2 single input deck

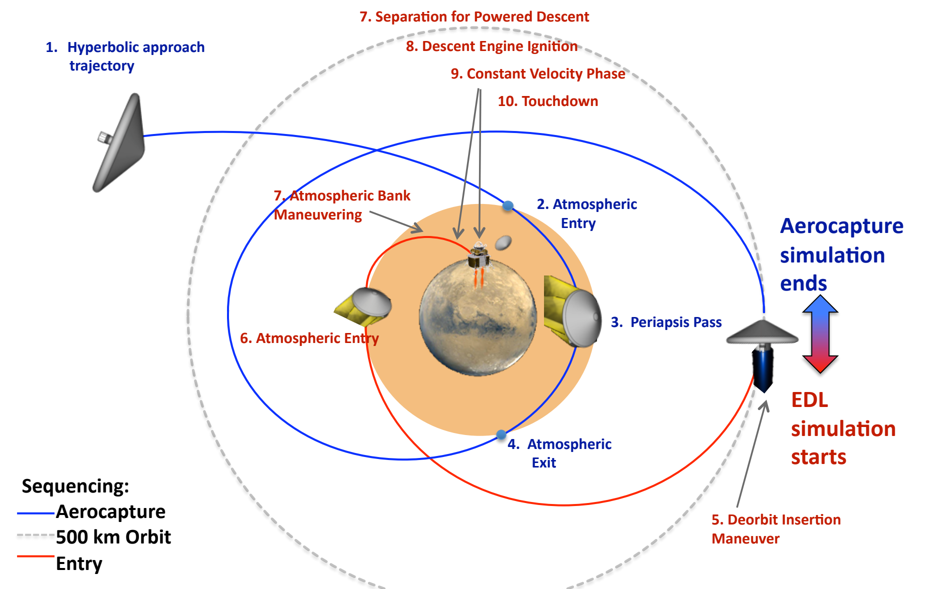
Simulation Model Status

EDL-SA



EFF Simulation Event Structure

EDL-SA



Summary

EDL-SA

- EDL-SA POST2 simulation has incorporated all Year 1 models along with many new models this year
- Longest lead items were checkouts of model implementation
  - Majority of (~80%) models included are checked out
- Configuration control software ClearCase has allowed multiple people to work on independent branches without disrupting core functionality for others
- Common use of inputs and simulation environment will ensure consistent comparison of results

EDL-SA

Backup

EDL-SA

Monte Carlo Inputs

```
//*********** AC & EDL Monte Carlo Inputs ************
// -----------------------
//  Initial State
// -----------------------
ac_gamei  -11.8063      +/- 0.25         normal
ac_hypvel  5463.59222    +/- 20.0         normal
ac_bpang   270.0          +/- 0.10        normal
ac_tof   -30.0            +/- 2.0      normal
edl_malta   500         +/- 0.0   normal
edl_maltp  -219.017015  +/- 0.0   normal
edl_inc     90          +/- 0.0   normal
edl_lan     3.3369132273595O337e+02          +/- 0.1   normal
edl_argp    4.44004987171960863e+01          +/- 0.1   normal
edl_lan_disp  0.0       +/- 0.1   normal
edl_argp_disp 0.0       +/- 0.1   normal
edl_truan   180         +/- 0.0   normal

// --------------------------------------
//  Initial Attitude/Rate Uncertainties
// --------------------------------------
ac_alpha           -18.0          +/- 0.25       normal
ac_beta            0.0            +/- 0.25       normal
ac_bnkang          0.0            +/- 0.25       normal
ac_rolbd           0.0            +/- 0.10       normal
ac_pitbd           0.0            +/- 0.10       normal
ac_yawbd           0.0            +/- 0.10       normal
edl_alpha          -18.0          +/- 0.25       normal
edl_beta           0.0            +/- 0.25       normal
edl_bnkang         0.0            +/- 0.25       normal
edl_rolbd          0.0            +/- 0.10       normal
edl_pitbd          0.0            +/- 0.10       normal
edl_yawbd          0.0            +/- 0.10       normal

// --------------------------------------
//  Atmospheric Uncertainties
// --------------------------------------
atm_rnd_num     1               1:29999        integer
tau             0.45            0.1:0.9        uniform
denkt           1.0             +/-15%         uniform
perts           0               1:1            uniform


// --------------------------------------
//  Aerodynamic Uncertainties
// --------------------------------------
ca_mult         1.0             0.90:1.1       normal
cn_mult         1.0             0.90:1.1       normal
cy_mult         1.0             0.90:1.1       normal
edl_alpha_add   0.0             +/- 1.0        normal

// --------------------------------------
//  Mass Property Uncertainties
// --------------------------------------
ac_xcgbias_ldp25  -0.22486        +/- 0.001      normal
ac_ycgbias_ldp25   0.0            +/- 0.001      normal
ac_zcgbias_ldp25   0.462          +/- 0.001      normal
ac_xcgbias_ldp1     -0.22486        +/- 0.001      normal
ac_ycgbias_ldp1      0.0            +/- 0.001      normal
ac_zcgbias_ldp1      0.175          +/- 0.001      normal
edl_xcgbias     -2.5145         +/- 0.001        normal
edl_ycgbias     0.0             +/- 0.001        normal
edl_zcgbias     0.2512          +/- 0.001        normal

// --------------------------------------
//  ALHAT IMU Uncertainties
// --------------------------------------
bias_acc_x      0               +/- 8.250E-04   normal
bias_acc_y      0               +/- 8.250E-04   normal
bias_acc_z      0               +/- 8.250E-04   normal
sf_acc_x        0               +/- 4.500E-04   normal
sf_acc_y        0               +/- 4.500E-04   normal
sf_acc_z        0               +/- 4.500E-04   normal
iseed_acc_x     1               1:29999         integer
iseed_acc_y     1               1:29999         integer
iseed_acc_z     1               1:29999         integer
rnoise_acc      0.0             9.0E-05:9.0E-05 uniform

bias_gyro_x     0               +/- 1.745E-07   normal
bias_gyro_y     0               +/- 1.745E-07   normal
bias_gyro_z     0               +/- 1.745E-07   normal
sf_gyro_x       0               +/- 2.700E-05   normal
sf_gyro_y       0               +/- 2.700E-05   normal
sf_gyro_z       0               +/- 2.700E-05   normal
iseed_gyro_x    1               1:29999         integer
iseed_gyro_y    1               1:29999         integer
iseed_gyro_z    1               1:29999         integer
rnoise_gyro     0.0             1.309E-07:1.309E-07     uniform

// --------------------------------------
//  ALHAT Star Camera Uncertainties
// --------------------------------------
iseed_st_x          1           1:29999         integer
iseed_st_y          1           1:29999         integer
iseed_st_z          1           1:29999         integer
bias_st_x           0.0      +/- 0.0               normal      # 3-sig, deg
bias_st_y           0.0      +/- 0.0              normal       # 3-sig, deg
bias_st_z           0.0      +/- 0.0              normal       # 3-sig, deg
rnoise_st           0.0         0.0:0.0        uniform

// --------------------------------------
//  ALHAT Altimeter Uncertainties
// --------------------------------------
iseed_alt            1           1:29999         integer
rnoise_alt           0.0         0.0:0.0       uniform

// --------------------------------------
//  ALHAT Velocimeter Uncertainties
// --------------------------------------
iseed_vel_horz      1           1:29999         integer
iseed_vel_vert      1           1:29999        integer
rnoise_vel_horz    0.0          0.0:0.0        normal
rnoise_vel_vert    0.0          0.0:0.0        normal

// --------------------------------------
//  Knowledge Uncertainties
// --------------------------------------
ac_xi_delta        0               +/- 2000       normal
ac_yi_delta        0               +/- 2000       normal
ac_zi_delta        0               +/- 2000       normal
ac_vxi_delta       0               +/- 2          normal
ac_vyi_delta       0               +/- 2          normal
ac_vzi_delta       0               +/- 2          normal
ac_ex              0.0             +/- 1.0        normal
ac_ey              0.0             +/- 1.0        normal
ac_ez              0.0             +/- 1.0        normal
ac_att_err_mag     0.0             0.0:1.0        uniform
edl_xi_delta       0               +/- 2000       normal
edl_yi_delta       0               +/- 2000       normal
edl_zi_delta       0               +/- 2000       normal
edl_vxi_delta      0               +/- 2          normal
edl_vyi_delta      0               +/- 2          normal
edl_vzi_delta      0               +/- 2          normal
edl_ex             0.0             +/- 0.1        normal
edl_ey             0.0             +/- 0.1        normal
edl_ez             0.0             +/- 0.1        normal
edl_att_err_mag    0.0             0.0:0.1        uniform
```

EFF Control Modes

EDL-SA

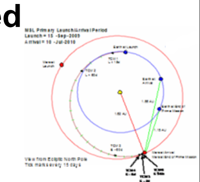
- Implemented framework for 3 control modes
  - Bank control
  - CG control
  - Combo control
- Work is progressing to standardize guidance commands to be vertical and horizontal L/D such that conversion to control and actuation is handled by the controller and not the guidance
- Each control method utilizes independent interface routines within POST
- All 3 control modes have been tested using HYPAS guidance

EFF Navigation & Sensors

EDL-SA

- Have only implemented ALHAT low-fi imu model
  - Includes scale factors, biases, and random noise

- NAVLRC package in POST has been incorporated to EDL-SA framework and is awaiting check-out
  - Includes built-in IMU and Startracker model
- Simple Nav propagator has been implemented
  - Propagates state using ALHAT IMU measurements
  - Allows modeling of knowledge and attitude errors



- ALHAT Nav filter
  - Simple Nav propagator and NAVLRC package will provide a baseline from which the ALHAT Nav filter can be measured

EFF Guidance Modes

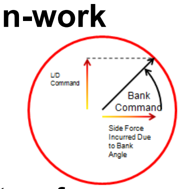
EDL-SA

- Various guidance algorithms have been implemented
  - HYPAS Aerocapture Guidance (Checked-Out)
  - Apollo Derived Aerocapture Guidance (Checked-Out)
  - Shape Integral Aerocapture Guidance (Checked-Out)
  - Numerical Predictor Corrector Aerocapture Guidance (Checked-Out)
  - Theoretical Entry Guidance (Checked-Out)
  - Apollo Entry Guidance (Checked-Out)
  - Theoretical Powered Descent Guidance (Checked-Out)
  - Apollo Powered Descent Guidance (Checked-Out)
  - Shape Integral Gravity Turn Guidance (Checked-Out)
- All guidances, except theoretical, utilize self contained independent structures with no knowledge of POST environment
  - Input data comes only from Nav

EFF Controllers & Actuators

EDL-SA

- Various controller models implemented or in-work
  - Aerodynamic Trim – Provides 3DOF alpha/beta
  - Pseudo Controller – Provides 3DOF actuation based on input rates and accelerations
  - LQR Controller – Provides 6DOF actuation of bank control using perfect torques
  - PID Controller – Provides 6DOF actuation of center of gravity

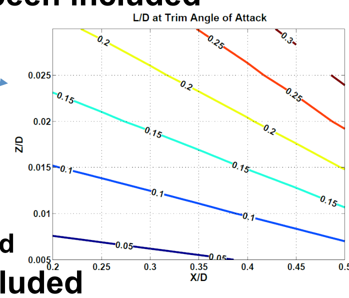


- Each controller model provides data for actuation
  - Perfect 6DOF actuation applies forces and moments to POST equations of motion
  - Perfect 3DOF actuation is applied through controller variables that are linked in the POST input deck, i.e. trim alpha, trim beta, and commanded bank angle multipliers
- Actuation models needing to be implemented
  - RCS thrust location and mixing logic
  - ALHAT based engine gimbal model

Auxiliary POST2 Models

EDL-SA

- David Way provided aerocapture delta-v calculations to ensure all GN&C methods are judged equally
- Samareh Mass Model
- Multiple aerodatabases have been included
  - MSL 70 deg sphere cone
  - Ames 65 degree sphere cone
  - Genesis 60 deg sphere cone
  - Orion (Apollo shape)
  - Ames HIAD (Apollo forebody)
  - Ames Rigid
  - MSLI tension cone and isotensoid



- Two parachute models are included
  - MSL disk-gap-band parachute model from Juan Cruz
  - CEV Parachute Assembly System (CPAS) reefed ringsail parachute model from Launch Abort System simulation

5.0 ALHAT Sensor Assessment Objectives and Overview

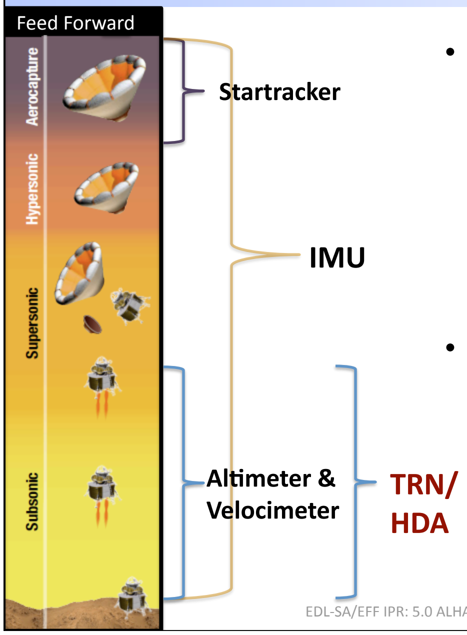
Jody L. Davis

Overview

- Objective: Develop a 6DOF entry simulation to determine the sensor performance ranges for an ALHAT-like navigation & sensor system at Mars
- EFF simulation developed and used to run initial integrated GNC & sensor performance and evaluation of SRP for Hazard Detection and Avoidance (HDA) & Terrain Relative Navigation (TRN)
  - 6DOF entry with Apollo entry guidance and LQR bank angle controller
  - 3DOF powered descent w/ Apollo powered descent guidance and pseudo controller
- ALHAT extended Kalman filter (EKF) delivery by contractor did not include TRN capability
  - Matlab filter code (as-delivered, 10/4/10) implemented in EFF POST2 simulation
- ALHAT assessments will be shown
  - ✓ Monte Carlos with initial results of fully integrated GNC system & sensor performance
  - ✓ SRP powered descent study and trajectory design for HDA & TRN
  - ✓ Time did not permit trades on sensor operation ON/OFF timing

Baseline and Trades

EDL-SA



- ALHAT Study Baseline
  - IMU
  - Star Tracker to Entry Interface
  - ALHAT Altimetry & Velocimetry starting at SRP phase (Engine Ignition)
  - No TRN
- Trades
  - TRN on during SRP phase only
  - HDA evaluation
  - Time not permitting any other trades

EFF EDL Simulation Models

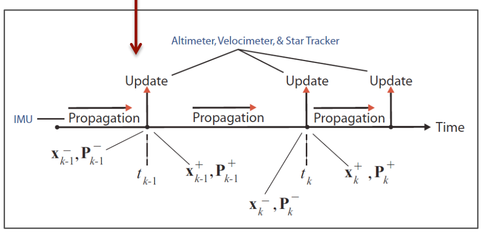
EDL-SA

- EFF simulation models used for ALHAT sensor assessment
  - ✓ Guidance algorithms: Apollo (entry & powered descent)
    - Powered descent utilizes constant throttle, throttle down and constant velocity phases
  - ✓ Control algorithms: 6DOF LQR (bank angle control)
  - ✓ Navigation filters: Simple propagator & ALHAT EKF
  - ✓ Sensor Models: IMU, startracker, velocimeter, altimeter
    - Models based on ALHAT project POST2 simulation
  - ✓ Aerodatabases: EFF 65-deg sphere cone (Ames)
  - ✓ Aerothermal Model: Ames
  - ✓ Mass properties from EFF Mass Model (Samareh)
    - CG, moments & products of inertia for each vehicle/component

Navigation Filter Model

EDL-SA

- **ALHAT Navigation algorithm in EFF simulation is dual-state extended Kalman filter (EKF)**
  - **Provides estimates of vehicle state (inertial position, velocity and attitude quaternion**
  - **Receives updates to improve state estimation from IMU, star tracker, altimeter/velocimeter**



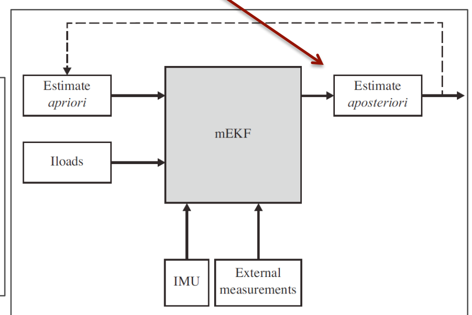


Figure 1: Multe-mode EKF Hierarchical Structure

Guidance & Controller Models

EDL-SA

- **Apollo Entry Guidance Algorithm**
  - **Modified Apollo entry guidance algorithm is closed-loop, reference approach defined by range-to-go, drag acceleration and altitude rate with respect to relative velocity**
- **LQR Bank Angle Entry Controller**
  - **6DOF linear quadratic regulator (LQR) control algorithm**
  - **Uses RCS torques to control Apollo guidance bank angle commands throughout range control phase of entry**
- **Apollo Powered Descent Guidance Algorithm with Pseudo Controller**
  - **Powered descent controlled by 2nd order polynomial in acceleration**
  - **Commanded acceleration vector given in LTF frame (defined by target and azimuth)**
  - **Control is handled in 3DOF by pseudo controller utilizing aero and Euler angles**
  - **Three powered descent phases: constant throttle, throttle-down & constant velocity**

IMU Model

EDL-SA

- Statistically-based Accelerometer and Gyroscope models take true (environment) body acceleration & body rates and adds random bias, noise & scale factor errors
- Converted to a delta-velocity & delta-angle to generate a measurement
- The Acceleration measurement model is given by:

$$\vec{a}_{acc} = \left(I_{3\times 3} + SF_{acc}\right)\vec{a}_{env} + b_{acc} + \eta_{acc}$$

$$\boxed{(\Delta - \bar{V})_k = \int_{t_{k-1}}^{t_k} \bar{a}_{acc} \cdot dt}$$

$$SF_{acc} = \begin{bmatrix} SF_{acc(x)} & 0 & 0 \\ 0 & SF_{acc(y)} & 0 \\ 0 & 0 & SF_{acc(z)} \end{bmatrix}, \quad \vec{b}_{acc} = \begin{bmatrix} b_{acc(x)} \\ b_{acc(y)} \\ b_{acc(z)} \end{bmatrix}, \quad \vec{\eta}_{acc} = \begin{bmatrix} \eta_{acc(x)} \\ \eta_{acc(y)} \\ \eta_{acc(z)} \end{bmatrix}$$

- Similarly, the Gyroscope measurement model is given by:

$$\vec{\omega}_{gyro} = \left(I_{3\times 3} + SF_{gyro}\right)\vec{\omega}_{env} + \vec{b}_{gyro} + \vec{\eta}_{gyro}$$

$$\boxed{(\Delta - \bar{\theta})_k = \int_{t_{k-1}}^{t_k} \bar{\omega}_{gyro} \cdot dt}$$

Startracker & TRN Model

EDL-SA

- Statistically-based Startracker model takes true attitude quaternion, bias and noise to generate measurements
- Noise (η_{st}) and bias (b_{st}) are used as such to calculate an error quaternion (q_e) via:

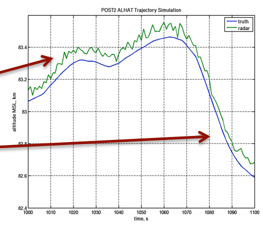
$$\bar{q}_{e(b,\eta)} = \begin{bmatrix} \cos\left(\frac{\beta_{st}}{2}\right) \\ \frac{\vec{\beta}_{st}}{\beta_{st}} \sin\left(\frac{\beta_{st}}{2}\right) \end{bmatrix}, \quad \vec{\beta}_{st} = \vec{\eta}_{st} + \vec{b}_{st}, \quad \beta_{st} = \left\|\vec{\beta}_{st}\right\|$$

$$\boxed{\bar{q}_{st} = \bar{q}_{e(b,\eta)}\bar{q}_{env}}$$

- Terrain relative navigation (TRN) is a terrain-mapping capability used for accomplishing safe, precision lunar landing
- Low-fidelity TRN model in POST2 determines vehicle position in pre-defined landing target frame (LTF) coordinate system
  - Returns 3D position in LTF frame
  - Random noise applied to measurement for dispersion analysis

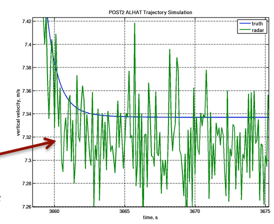
Altimeter & Velocimeter Model

- Altimeter model is currently a Nadir-pointing, statistically based model, including bias, noise and scale factor



$$h_{sensor} = h_{truth}\ (\ 1 + SF_h\ ) + (\ p_{noise}\ h_{truth} + h_{noise}\ ) + h_{bias}$$

where h_{truth} is the truth altitude (wrt spheroid or topography) and p_{noise}, h_{noise}, h_{bias}, and SF_h are noise percentage, noise addition, bias, and scale factor errors



- Velocimeter model is currently a relative-velocity, statistically based model, including bias, noise and scale factor

$$v_{sensor} = v_{truth}\ (\ 1 + SF_v\ ) + (\ p_{noise}\ v_{truth} + v_{noise}\ ) + v_{bias}$$

where v_{truth} is the truth horizonal or vertical velocity and p_{noise}, v_{noise}, v_{bias}, and SF_v are the noise percentage, noise addition, bias, and scale factor errors

Summary

- EFF simulation has been developed for 6DOF guided & controlled entry with 3DOF guided powered descent
- ALHAT-based extended Kalman navigation filter in simulation and running
  - Delivery from contractor did *not* include TRN update capability
- Initial ALHAT sensor assessment will be provided
- Up next…..
  - ✓ Apollo guidance and 6DOF LQR controller performance assessment
    - 6DOF entry Monte Carlo input descriptions and results
  - ✓ Study performed for powered descent evaluating SRP timeline and trajectory design for sensor feasibility
    - 3DOF descent Monte Carlo results and flight condition assessment for HDA & TRN
  - ✓ Initial ALHAT EKF navigation & sensor performance assessment using 6DOF entry/3DOF descent Monte Carlos
    - No TRN case vs. mimicked-TRN case for comparison

5.1 EDL-SA Feed Forward
Apollo Entry Guidance Performance

Eduardo García Llama

Objective

- Show entry guidance performance in presence of dispersions
- Demonstrate that the entry design is such that powered descent cases can be landed successfully

Nominal Configuration, Entry Conditions and Simulation Details

EDL-SA

- Nominal configuration
  - HIAD diameter = 8 m
  - Ballistic coefficient = 80 kg/m^2
  - L/D = 0.25
    - 65-deg sphere cone aerodynamics database by D. Kinney
  - Bank control
    - Maximum bank acceleration = 5 deg/s^2
    - Maximum bank rate = 20 deg/s
- Entry conditions
  - Entry velocity is 3.5 km/s (at 125 km)
  - Entry mass = 5580 kg
  - Entry flight path angle = -5.63 deg
- Simulation details
  - Mars GRAM 2005 atmosphere
  - Mars 85x85 gravitational model
  - Terrain model: 1/32nd deg MOLA Data
  - 6 DOF
  - Simple propagator navigation

Guidance Overview

EDL-SA

- Guidance is the Apollo final phase analytical predictor/corrector scheme
- Comprised by 2 phases
  - Range control phase
  - Heading alignment phase
- Range control phase
  - Varies the bank angle to control range based on deviations in range, altitude rate and drag acceleration from a stored reference trajectory
  - Does not try to follow the reference trajectory in dispersed conditions, instead steers a trajectory that should have nearly the same terminal conditions
  - Commands bank reversals to control crossrange when reversal deadband is reached
  - Control gains are derived using linear perturbation theory with the reference trajectory by reverse integration of the differential equations adjoint to the linearized equations of motion

Predict Current Range To-Go: $R_p = R_{ref} + \frac{\partial R}{\partial D}(D - D_{ref}) - \frac{\partial R}{\partial \dot{r}}(\dot{r} - \dot{r}_{ref})$

Find Commanded Vertical L/D to Converge Range Error: $\left(\frac{L}{D}\right)_{V,C} = \left(\frac{L}{D}\right)_{V,ref} + \frac{K3(R - R_p)}{\partial R/\partial (L/D)_V}$

Bank Required For Commanded L/D: $\Phi_C = \cos^{-1}\left(\frac{(L/D)_{V,C}}{(L/D)}\right) \times K2_{roll}$

R	Range
R_p	Range, predicted
R_{ref}	Range, reference
D	Drag
D_{ref}	Drag, reference
L	Lift
r	Altitude Rate
r_{ref}	Altitude Rate, ref
K3	L/D over-control gain
$K2_{roll}$	Bank sign (left or right)

Guidance Overview (cont.)

EDL-SA

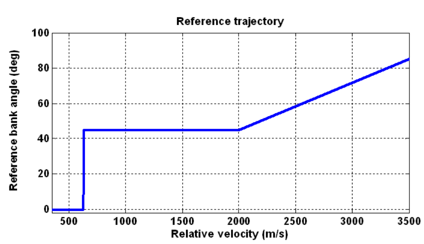
- <u>Heading alignment phase</u>
  - Initiated at low velocity to drive azimuth error to zero at engine initiation
  - Commanded bank angle is proportional to the current azimuth error to the target

$$\Phi_C = \tan^{-1}\left(\frac{crossrange}{downrange}\right) \times K4$$

K4 is the over-control gain

Generation of the Reference Profile

EDL-SA

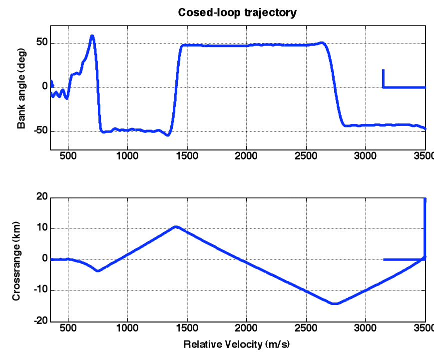


- Variable bank reference trajectories result in smaller velocity at a given altitude than constant bank
- Previous experience shows that minimum bank in region with constant bank should be given by ϕ_{min} = acos(100%-$\rho_{\%}$-$C_{d\%}$)
  - $\phi_{min\ EDL\text{-}SA\ FF}$ = acos(100%-15%-10%) = 41.4°
- Constant bank selected = 45°
- Heading control alignment phase starts at 630 m/s (M = 2.8)
  - Terminal velocity at separation is 346 m/s (M = 1.5)

Closed Loop Trajectory

EDL-SA

- Lateral corridor determined such that the number of reversals is 3
  - Corridor is determined as a quadratic function of the velocity through
    - 2 bank reversal deadband quadratic coefficients
    - deadband constant coefficient
- Condition to end simulation is based on downrange
- Nominal final altitude is determined such that all the powered descent dispersed cases are successful



Monte Carlo Inputs (Entry)

EDL-SA

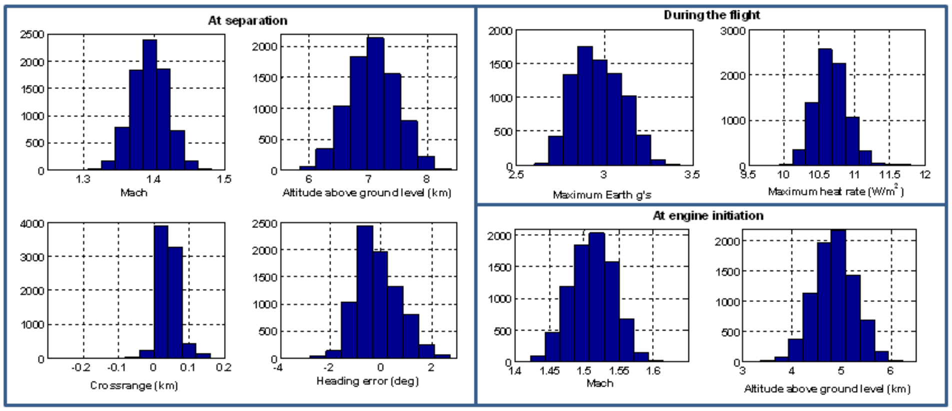
Longitude of the ascending node
Argument of the perigee
Roll body rate
Pitch body rate
Yaw body rate
Mars GRAM 2005 perturbations
Mars GRAM winds
Density
Perts – To run perturbed atmosphere

```
//*********** AC & EDL Monte Carlo Inputs ************
// ------------------------
//  Initial State
// ------------------------
ac_gamei  -11.8063      +/- 0.25        normal
ac_hypvel  5463.59222    +/- 20.0        normal
ac_bpang   270.0          +/- 0.10       normal
ac_tof   -30.0            +/- 2.0      normal
edl_malta   500         +/- 0.0   normal
edl_maltp  -219.017015  +/- 0.0   normal
edl_inc     90          +/- 0.0   normal
edl_lan     3.33691322735950337e+02        +/- 0.1   normal
edl_argp    4.44004987171960863e+01        +/- 0.1   normal
edl_lan_disp  0.0       +/- 0.1   normal
edl_argp_disp 0.0       +/- 0.1   normal
edl_truan   180         +/- 0.0   normal

// ---------------------------------------
//  Initial Attitude/Rate Uncertainties
// ---------------------------------------
ac_alpha          -18.0          +/- 0.25        normal
ac_beta           0.0            +/- 0.25        normal
ac_bnkang         0.0            +/- 0.25        normal
ac_rolbd          0.0            +/- 0.10        normal
ac_pitbd          0.0            +/- 0.10        normal
ac_yawbd          0.0            +/- 0.10        normal
edl_alpha         -18.0          +/- 0.25        normal
edl_beta          0.0            +/- 0.25        normal
edl_bnkang        0.0            +/- 0.25        normal
edl_rolbd         0.0            +/- 0.10        normal
edl_pitbd         0.0            +/- 0.10        normal
edl_yawbd         0.0            +/- 0.10        normal

// ---------------------------------------
//  Atmospheric Uncertainties
// ---------------------------------------
atm_rnd_num     1               1:29999         integer
tau             0.45            0.1:0.9         uniform
denkt           1.0             +/-15%          uniform
perts           0               1:1             uniform


// ---------------------------------------
//  Aerodynamic Uncertainties
// ---------------------------------------
ca_mult         1.0             0.90:1.1        normal
cn_mult         1.0             0.90:1.1        normal
cy_mult         1.0             0.90:1.1        normal
edl_alpha_add   0.0             +/- 1.0         normal

// ---------------------------------------
//  Mass Property Uncertainties
// ---------------------------------------
ac_xcgbias_ldp25  -0.22486        +/- 0.001       normal
ac_ycgbias_ldp25   0.0            +/- 0.001       normal
ac_zcgbias_ldp25   0.462          +/- 0.001       normal
ac_xcgbias_ldp1    -0.22486        +/- 0.001       normal
ac_ycgbias_ldp1     0.0            +/- 0.001       normal
ac_zcgbias_ldp1     0.175          +/- 0.001       normal
edl_xcgbias     -2.5145        +/- 0.001         normal
edl_ycgbias      0.0           +/- 0.001         normal
edl_zcgbias      0.2512        +/- 0.001         normal

// ---------------------------------------
//  ALHAT IMU Uncertainties
// ---------------------------------------
bias_acc_x      0               +/- 8.250E-04   normal
bias_acc_y      0               +/- 8.250E-04   normal
bias_acc_z      0               +/- 8.250E-04   normal
sf_acc_x        0               +/- 4.500E-04   normal
sf_acc_y        0               +/- 4.500E-04   normal
sf_acc_z        0               +/- 4.500E-04   normal
iseed_acc_x     1               1:29999         integer
iseed_acc_y     1               1:29999         integer
iseed_acc_z     1               1:29999         integer
rnoise_acc      0.0             9.0E-05:9.0E-05 uniform

bias_gyro_x     0               +/- 1.745E-07   normal
bias_gyro_y     0               +/- 1.745E-07   normal
bias_gyro_z     0               +/- 1.745E-07   normal
sf_gyro_x       0               +/- 2.700E-05   normal
sf_gyro_y       0               +/- 2.700E-05   normal
sf_gyro_z       0               +/- 2.700E-05   normal
iseed_gyro_x    1               1:29999         integer
iseed_gyro_y    1               1:29999         integer
iseed_gyro_z    1               1:29999         integer
rnoise_gyro     0.0             1.309E-07:1.309E-07     uniform

// ---------------------------------------
//  ALHAT Star Camera Uncertainties
// ---------------------------------------
iseed_st_x        1             1:29999         integer
iseed_st_y        1             1:29999         integer
iseed_st_z        1             1:29999         integer
bias_st_x         0.0      +/- 0.0                normal      # 3-sig, deg
bias_st_y         0.0      +/- 0.0               normal      # 3-sig, deg
bias_st_z         0.0      +/- 0.0               normal      # 3-sig, deg
rnoise_st         0.0         0.0:0.0         uniform

// ---------------------------------------
//  ALHAT Altimeter Uncertainties
// ---------------------------------------
iseed_alt           1           1:29999         integer
rnoise_alt          0.0         0.0:0.0       uniform

// ---------------------------------------
//  ALHAT Velocimeter Uncertainties
// ---------------------------------------
iseed_vel_horz      1           1:29999         integer
iseed_vel_vert      1           1:29999         integer
rnoise_vel_horz   0.0           0.0:0.0         normal
rnoise_vel_vert   0.0           0.0:0.0         normal

// ---------------------------------------
//  Knowledge Uncertainties
// ---------------------------------------
ac_xi_delta       0             +/- 2000        normal
ac_yi_delta       0             +/- 2000        normal
ac_zi_delta       0             +/- 2000        normal
ac_vxi_delta      0             +/- 2           normal
ac_vyi_delta      0             +/- 2           normal
ac_vzi_delta      0             +/- 2           normal
ac_ex             0.0           +/- 1.0         normal
ac_ey             0.0           +/- 1.0         normal
ac_ez             0.0           +/- 1.0         normal
ac_att_err_mag    0.0           0.0:1.0         uniform
edl_xi_delta      0             +/- 2000        normal
edl_yi_delta      0             +/- 2000        normal
edl_zi_delta      0             +/- 2000        normal
edl_vxi_delta     0             +/- 2           normal
edl_vyi_delta     0             +/- 2           normal
edl_vzi_delta     0             +/- 2           normal
edl_ex            0.0           +/- 0.1         normal
edl_ey            0.0           +/- 0.1         normal
edl_ez            0.0           +/- 0.1         normal
edl_att_err_mag   0.0           0.0:0.1         uniform
```

Monte Carlo Results (8000 Cases)

EDL-SA

Downrange error is not shown because the simulation end condition is based on range, thus, the downrange error is very small at separation. Downrange error at engine initiation is within ±200 m



Conclusion

EDL-SA

- Under dispersions, the Apollo entry guidance is capable of achieving the engine initiation conditions such that all the powered descent dispersed cases can be landed successfully.
- There is room to improve
  - Improve reference profile
  - Improve overcontrol settings
  - Selection of initial flight path angle
  - Set drag acceleration and L/D filter time constants, drag and altitude controller gain scale factors
  - Fine tuning of all the parameters

5.2 Powered Descent Performance

Ron Sostaric
Jeremy Shidner
Eduardo Llama

Objectives

- Show Powered Descent performance
- Show flight condition and timing of TRN
- Show flight condition and timing of HDA

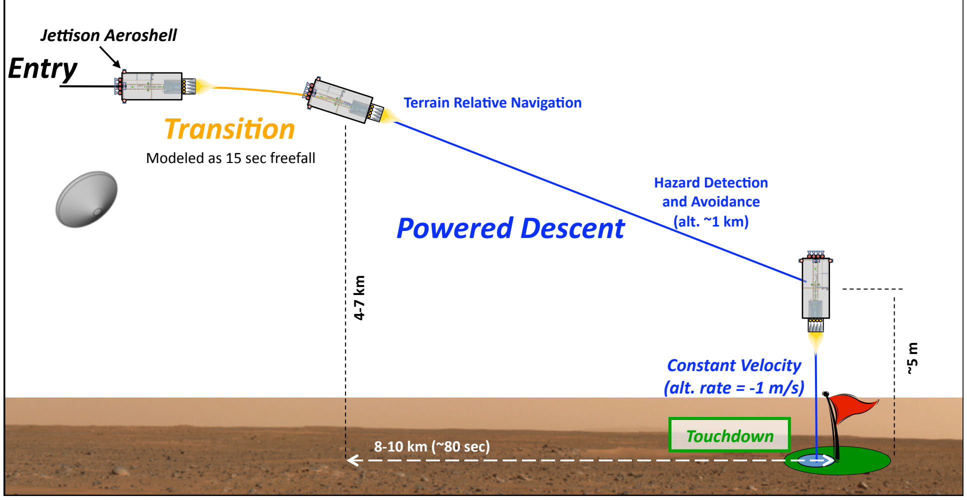
Powered Descent Simulation Assumptions

EDL-SA

- Powered descent guidance law is a 2^{nd} order polynomial in acceleration
  - Total Acceleration = $A + Bt + Ct^2 + g$
  - Integrate 2^{nd} order polynomial to get position and velocity as a function of time
  - Final time represents guidance targets determined from 3DOF reference trajectory
  - Current time utilizes navigated position and velocity
  - Targeted profile yields appropriate acceleration gain coefficients A, B, and C
  - Commanded acceleration vector given in LTF frame
- Landing Target Frame (LTF) defined according to target and azimuth
  - Origin is placed at target given longitude, planetodetic latitude, and planetodetic altitude
  - Navigated position is derived relative to target in planet fixed frame
  - Position is rotated to LTF frame by a 3-2-1 rotation in longitude, -latitude, and –azimuth respectively
  - Resulting state is in terms of Altitude (X), Crossrange (Y), and Downrange (Z)
- Control is handled in 3DOF by pseudo controller utilizing aero and euler angles
  - Pseudo controller enforces 20 deg/s and 5 deg/s^2 rate limits
  - 15 second transition event commands 0 degree relative alpha and beta prior to engine ignition
  - Post engine ignition, vehicle is controlled by inertial euler angles in pitch, yaw, and roll
  - Constant velocity phase sets rate limits to instantaneous to avoid guidance instabilities
- Powered descent utilizes three phases
  - Constant throttle phase
  - Throttle down phase
  - Constant velocity phase

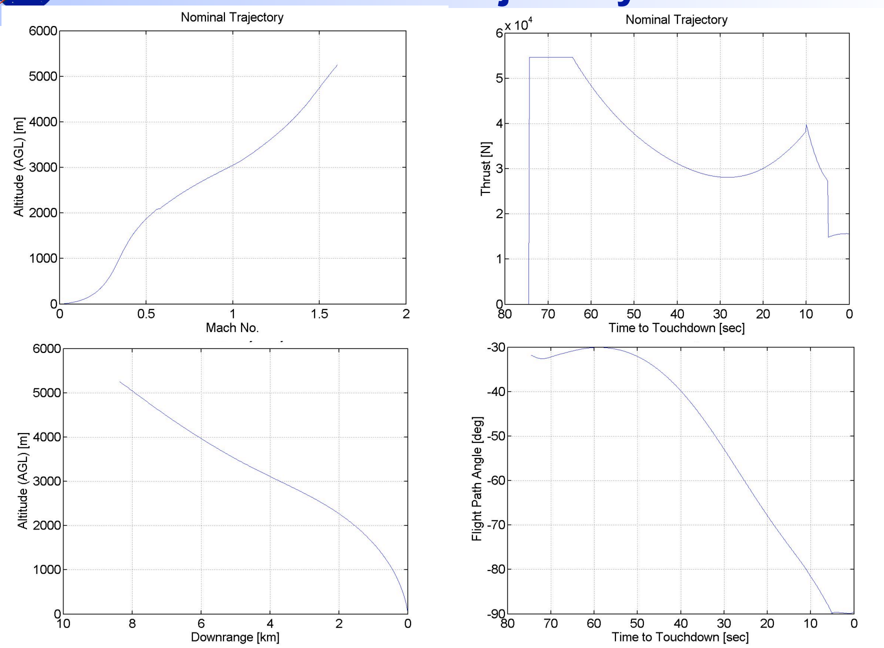
Powered Descent

EDL-SA



Nominal Trajectory

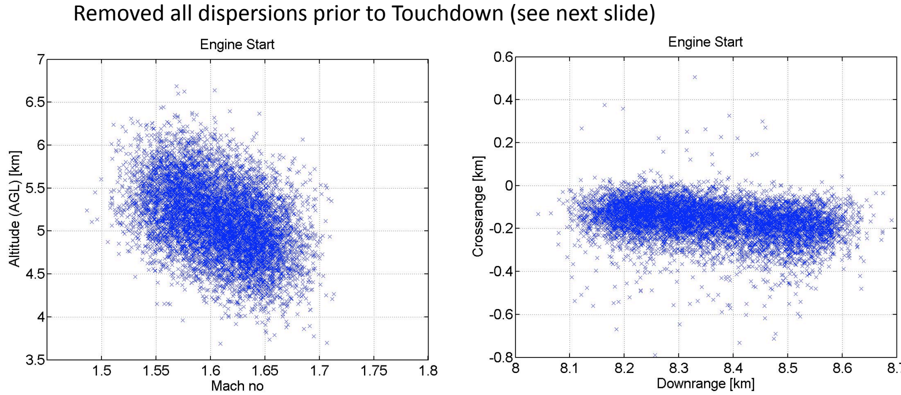
EDL-SA



Monte Carlo Results – Engine Start

EDL-SA

Perfect navigation starting at aeroshell separation
Removed all dispersions prior to Touchdown (see next slide)

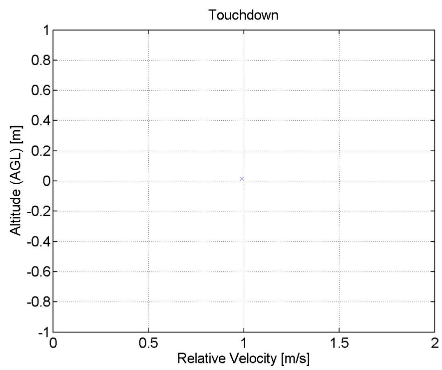


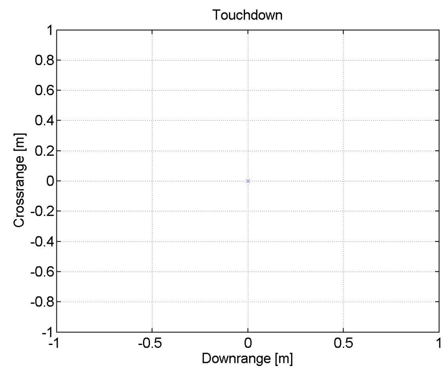
Monte Carlo Results – Touchdown

EDL-SA

Perfect Navigation

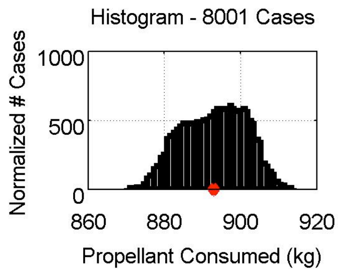
All 8000 cases landed successfully with 1 m/s velocity

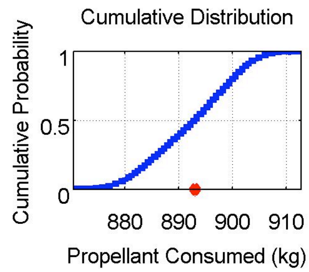




Monte Carlo Results

EDL-SA



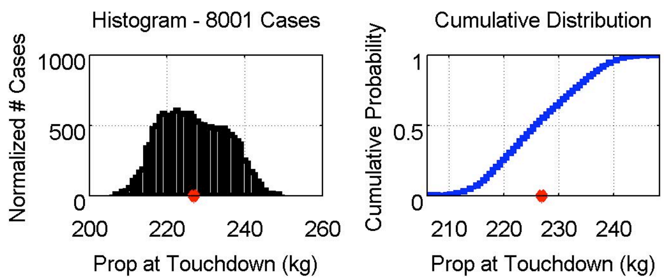


Statistics for
Propellant Consumed (kg):

Mean = 893.0261 → ΔV=588 m/s
1-Sigma = 8.0956
3-Sigma = 24.2868
Minimum = 870.3555
00.13 %-tile = 872.8781
50.00 %-tile = 893.4849
99.87 %-tile = 911.6812
Maximum = 914.0066

Monte Carlo Results

EDL-SA



Statistics for
Prop at Touchdown (kg):

Mean = 226.9282
1-Sigma = 8.0956
3-Sigma = 24.2868
Minimum = 205.9476
00.13 %-tile = 208.2731
50.00 %-tile = 226.4694
99.87 %-tile = 247.0762
Maximum = 249.5988

EDL-SA

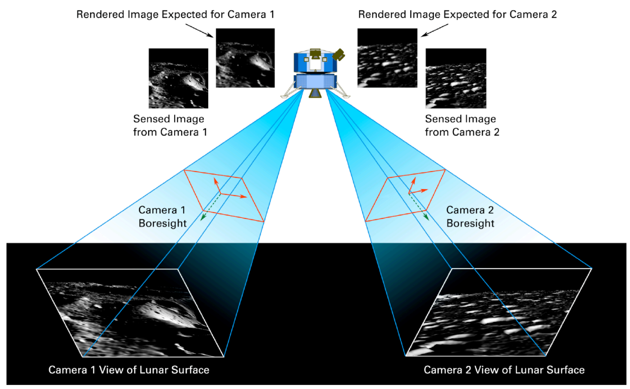
Trajectory Design for TRN and HDA

Terrain Relative Navigation

EDL-SA

- Terrain Relative Navigation (TRN) is ALHAT's chosen method to enable precision landing (in addition to standard EDL GN&C sensor capability)
- Basic idea is to use either passive optical or active sensing to provide a state update
- Multiple TRN algorithms encompassing both active and optical sensing are being studied by the ALHAT TSAR group
- Objective of this presentation is to show initial feasibility given the flight envelope of the powered descent

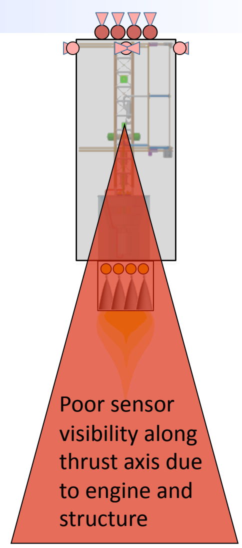
APLNav



TRN Feasibility

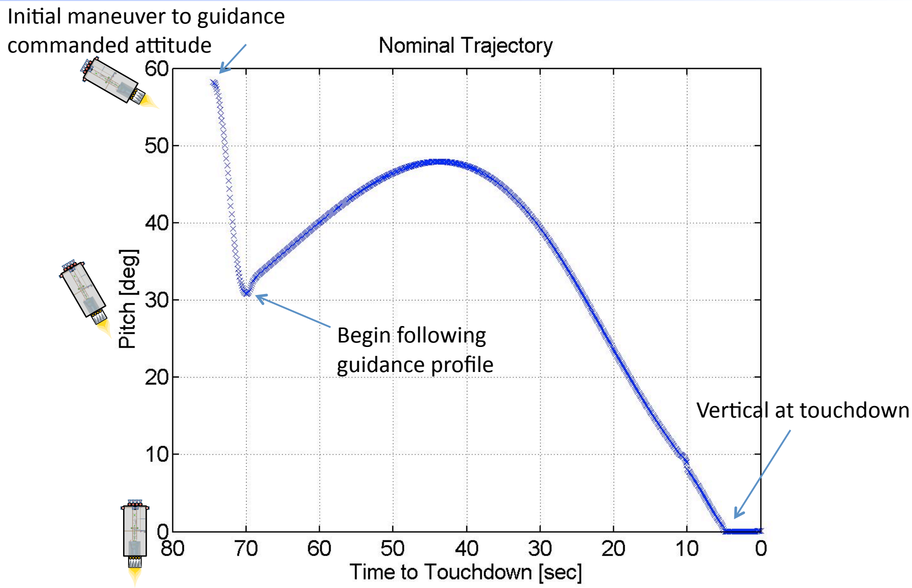
EDL-SA

- TRN works over a wide range of altitude and velocity
- Needs to see the ground
- Prefer to have the TRN measurement update as early as possible for dispersion control



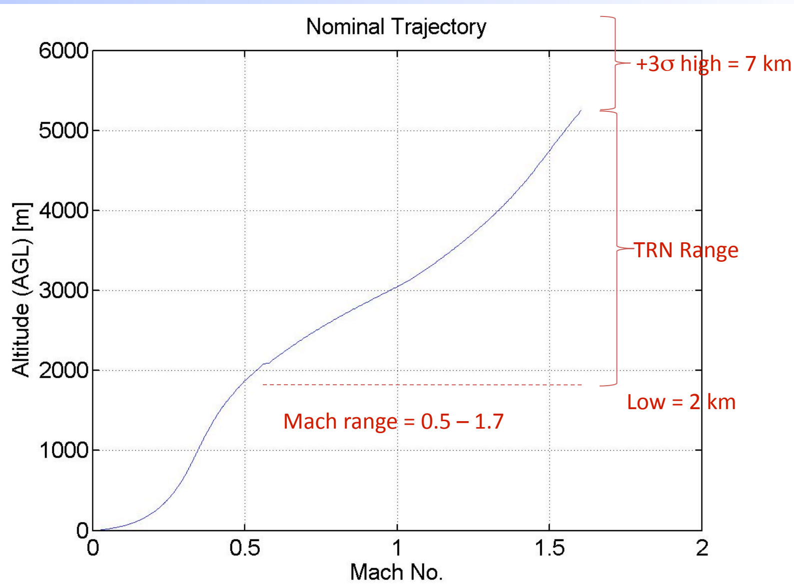
Powered Descent Nominal

EDL-SA



Powered Descent Nominal

EDL-SA



TRN Conclusions

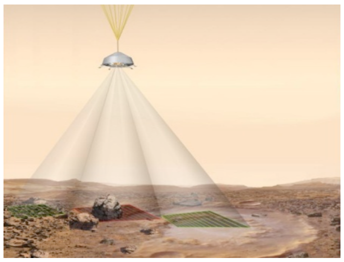
EDL-SA

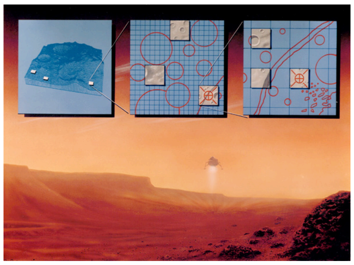
- Powered Descent trajectory is conducive to conducting TRN measurements
- Expected states and ranges
  - Altitude: 2 – 7 km
  - Velocity: Mach 0.5 – 1.7
  - Attitude
    - Attitude profile is not close to vertical and a continuous or near-continuous view of the ground is likely
  - Attitude Rate
    - No known concern
- Future work
  - Simulate effect of TRN (timing and nav performance)

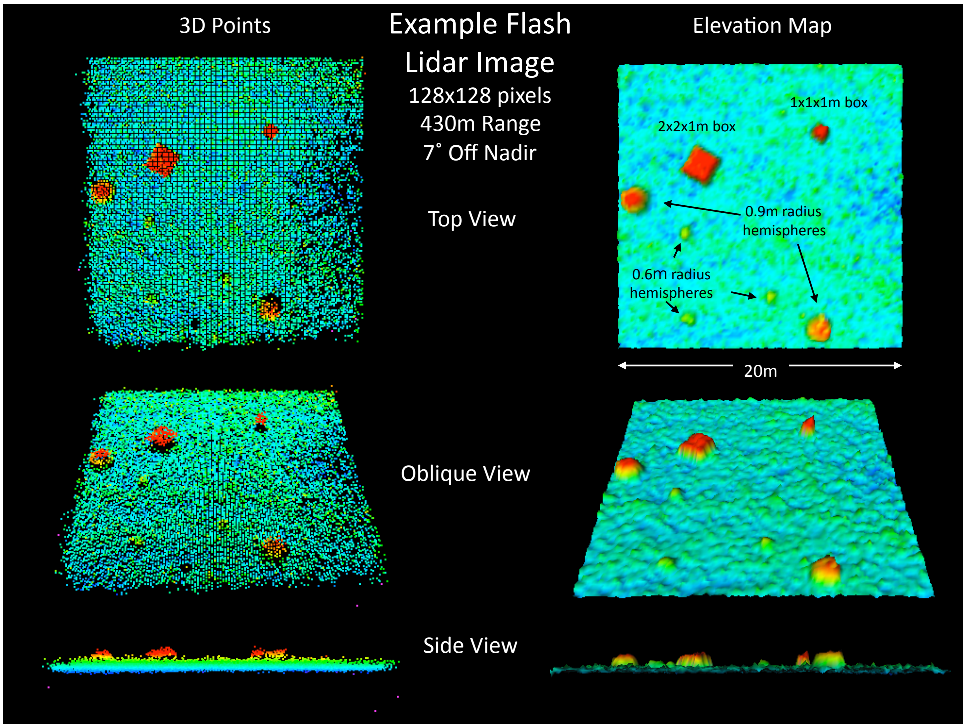
Hazard Detection and Avoidance (HDA)

EDL-SA

- HDA is the capability to detect and avoid hazards during the landing
- An onboard hazard map is developed real time during the descent using flash LIDAR
- The flash LIDAR returns a 3-D image of the landing area which contains higher resolution information of the landing area than currently possible using orbit reconnaissance
- An updated landing point is then selected (either automatically or via crew intervention) and the vehicle re-targets to the new landing point



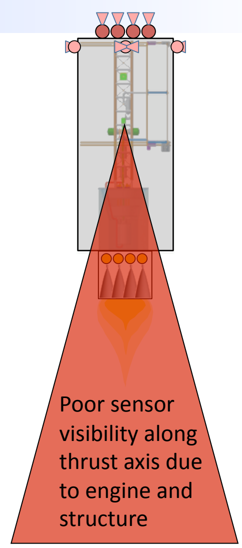




HDA Feasibility

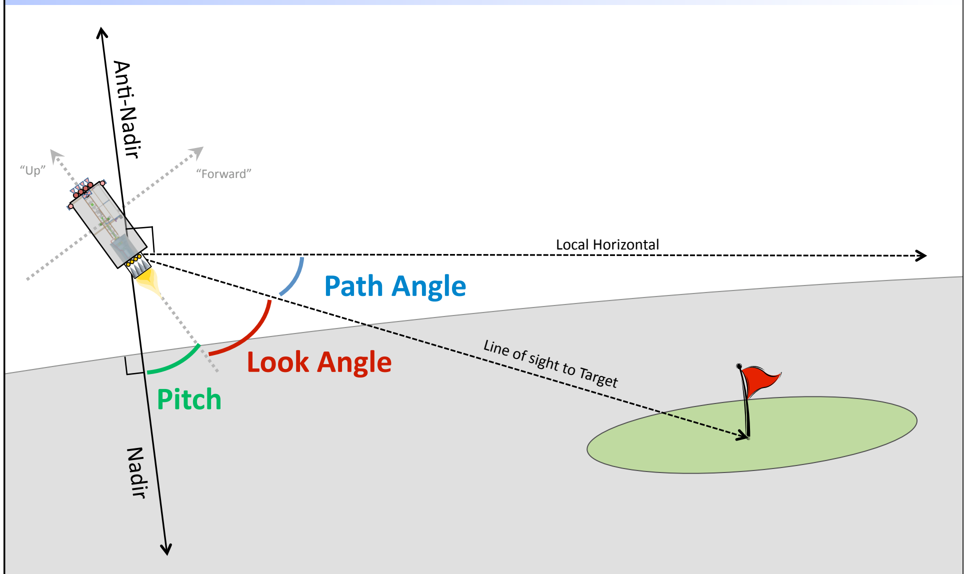
EDL-SA

- **HDA works over a limited range of altitude and velocity**
  - **Flash lidar system will be designed to work at a particular range (max 1-2 km)**
- **Needs to see the landing site at the correct time**
  - **Stricter criteria than for TRN**



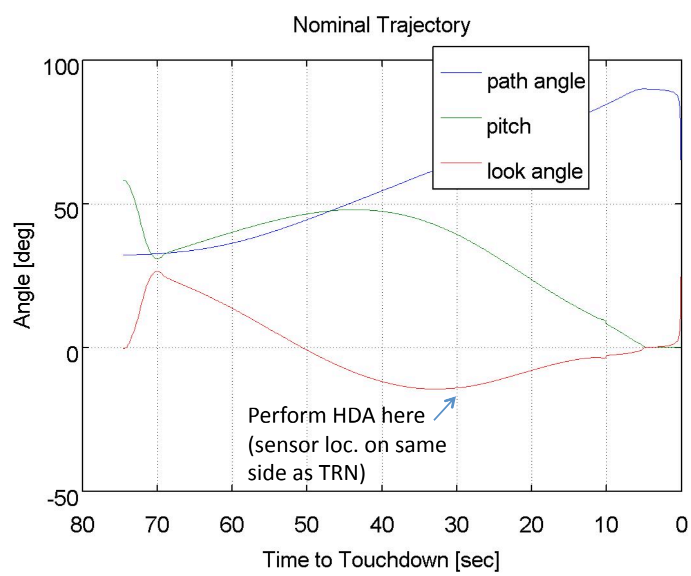
Angles of Interest During Landing

EDL-SA



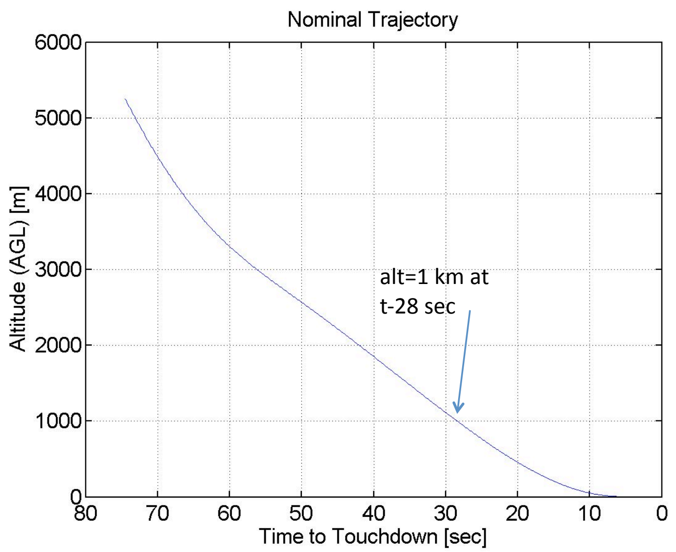
Powered Descent Nominal

EDL-SA



Powered Descent Nominal

EDL-SA



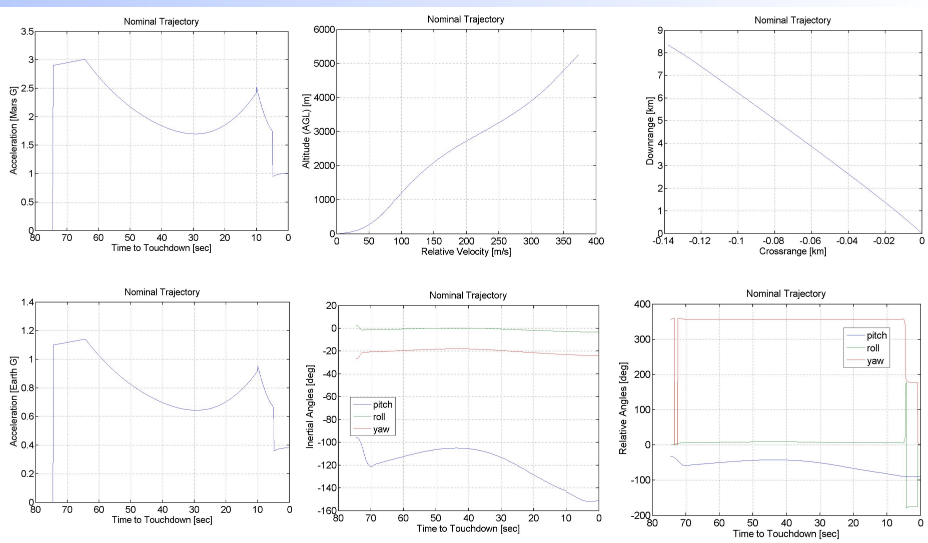
HDA Conclusions

EDL-SA

- Powered Descent trajectory for HDA needs further work
  - Current trajectory design may be a workable solution, but warrants additional investigation
  - Multi-year effort to develop Lunar HDA concept for ALHAT
- Current trajectory nominal HDA flight condition
  - Altitude = 1 km
  - Look angle = -14 deg
  - Path angle = 66 deg
- Can adjust nominal trajectory design to provide conditions for HDA
  - May want to consider lower throttle near touchdown for more time to divert
  - May want to consider biasing target uprange for positive look angle
- Need to look at dispersed HDA conditions
  - First need to define conditions of interest
  - Example: dispersed look angle at alt = 1 km
  - Uprange biasing may help keep dispersed look angles stay the same sign (single sensor location)
- Future work: Perform parametric divert study with redesigned profile

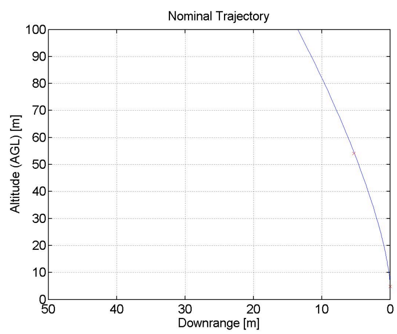
BACKUP

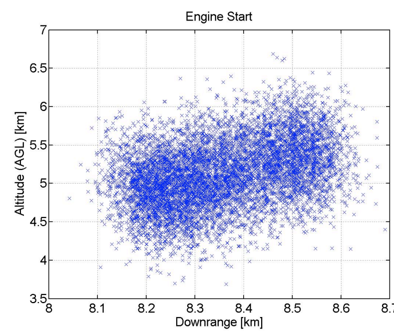
Nominal Trajectory



Nominal Trajectory

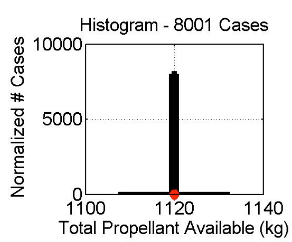
EDL-SA

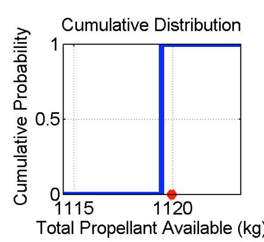




Monte Carlo Results

EDL-SA



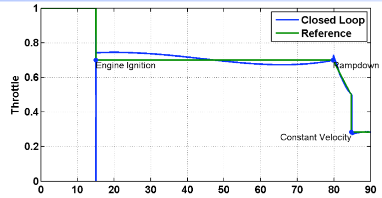


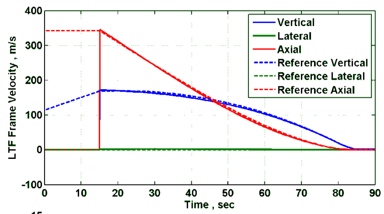
Statistics for
Total Propellant Available (kg):

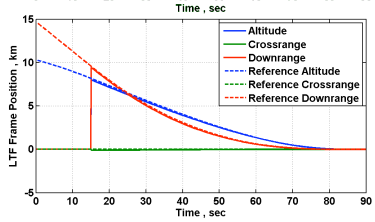
Mean = 1119.9543
1-Sigma = 4.0702e-011
3-Sigma = 1.2211e-010
Minimum = 1119.9543
Maximum = 1119.9543
Min. Case = 1
Max. Case = 1

Powered Descent Walkthrough

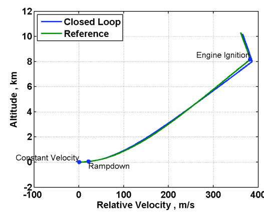
EDL-SA

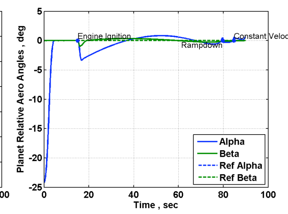






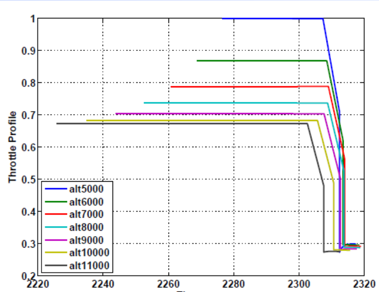
- Reference trajectory run first in 3DOF using nominal throttle profile
  - Assumes zero alpha and beta
  - Must account for dispersions
  - Determines position, velocity, and acceleration targets in LTF frame
- Engine ignition condition a function of entry guidance performance
  - Nominal Mach = 1.685
  - Nominal Altitude = 7.6 km
  - Nominal Downrange = 9.4 km
  - Nominal Crossrange = 0.0 km (Tailorable using entry guidance crossrange bias to achieve divert capability)
- Nominal timeline is 74.7 seconds
- Nominal fuel usage is 904 kg



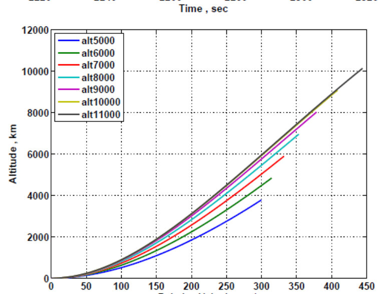


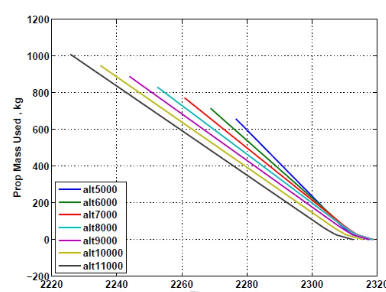
Backup Reference Tuning

EDL-SA



- Shortening timeline requires less fuel at the expense of margin in powered descent.
  - Reducing accuracy requirements could help to achieve lower prop mass
- Increasing HIAD size would help decrease engine ignition mach
  - Could possibly lose supersonic retropropulsion demonstration

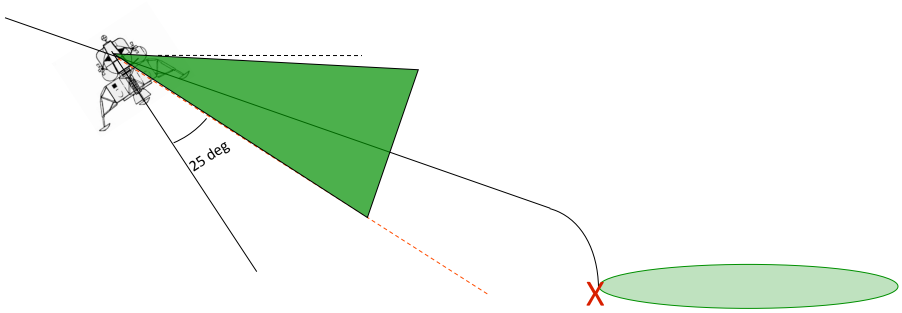




Designing for a window view

EDL-SA

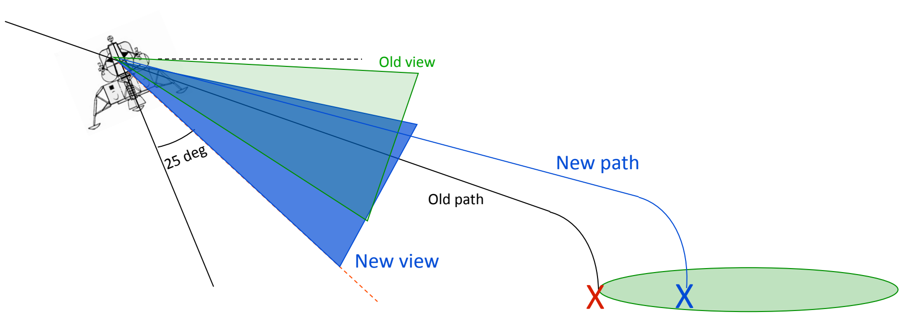
- **Trajectory path designed to (nearly) constant attitude during Approach Phase**
- **Target such that the entire landing footprint lies forward from the unredesignated landing site**



Designing for a window view

EDL-SA

- **Trajectory path designed to (almost) constant attitude during Approach Phase**
- **Target such that the entire landing footprint lies forward from the unredesignated landing site**



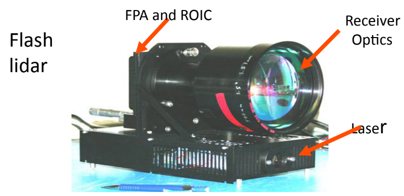
Diverting long improves your view, by rotating the vehicle attitude more toward vertical, and increasing look angle

SENSORS

EDL-SA

Under development by ALHAT

- ***3-D Flash Lidar:***
  - **HDA/HRN (1000 m to 100 m)**
  - **TRN (15 km to 2 km)**
  - **Altimetry (20 km to 100 m)**
- ***Doppler Lidar:* Velocity and Altitude (2500 m to 10 m)**
- ***Laser Altimeter:* Altitude Measurements (20 km to 2 km)**

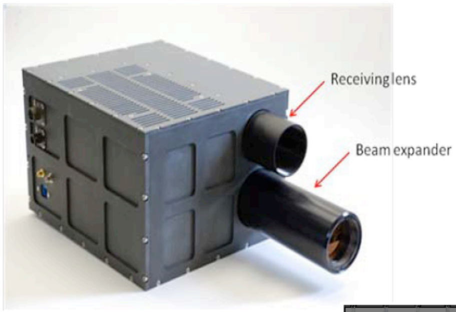


COTS with some modifications

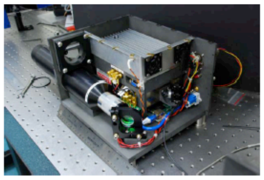
- ***Optical Camera:* TRN**

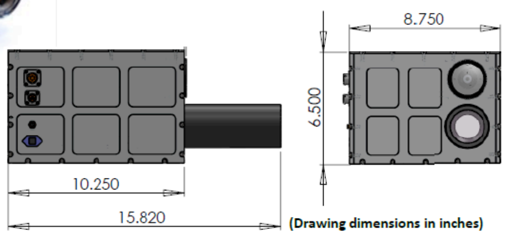
Laser Altimeter

EDL-SA



Partially assembled





(Drawing dimensions in inches)

Laser Altimeter Specifications

EDL-SA

Parameter	Measured	Goal
Maximum Operational Range	30 km	10 km
Accuracy	0.0034% of range	0.0034% of range
Precision	8 cm	20 cm
Data Update Rate	30 Hz	30 Hz

Outputs:
- Real time range measurement (up to 3 range measurements per pulse)
- Amplitude count
- Pulse count
- Time stamp

Input:
- 28 V, 3 A
- Average power 34 W

Weight : 10.24 kg

Laser Altimeter meets or exceeds all performance and physical goals

Doppler Lidar Specifications

EDL-SA

Parameter		Value	Goal
LOS Velocity Error		0.1 cm/sec	1 cm/sec
LOS Range Error		2 cm	10 cm/sec
Operational Altitude Range		2000 m w/ 1" lens 3500 m w/ 2" lens	2500 m
Data Acquisition Rate[1]		20 Hz, all raw data	30 Hz, all raw data
Power		110 W	150 W
Mass		14 kg	12 kg
Size	Electronics	17" x 13" x 7"	19" x 16" x 9"
	1" Optical Head	6" dia x 5" H	
	2" Optical Head	8" dia x 12" H	10" dia x 8" H

1. The data rate was changed from 30 Hz to 20 Hz to accommodate the raw data storage. High-rate real-time FPGA processor maybe in some of the flight.

Doppler Lidar meets or exceeds all performance and physical goals

Flash Lidars

EDL-SA

Variable FOV Flash Lidar

Fixed FOV Flash Lidar

Flash Lidar Rack

Flash Lidars on Gimbal

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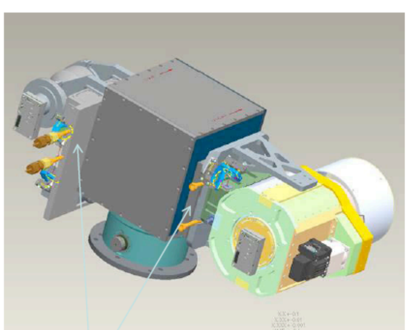
Mass Estimates including the baseplates:

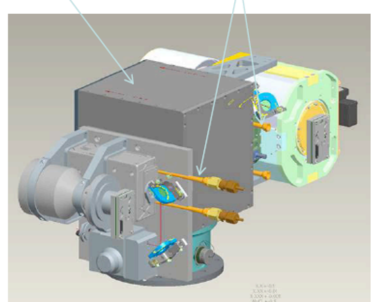
- Variable FOV Optic Flash Lidar 54.7 lbs
- Fixed Optic Flash Lidar 26.1 lbs



Baseplates serve as both Gimbal mechanical and thermal interface

Gimbal

Chiller Liquid Lines



Measured Flash Lidar Performance

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Parameter	FT1 and FT3 (GEN 1)	FT4 (GEN 2)	FT4 (Fixed-optic)	Goal (Fixed-optic)
Max operational range	420 m	1300 m	2000 m	1200 m
FOV	3 deg	Variable 6 – 24 deg	1 deg	1 deg
Precision	8 cm	8 cm	8 cm	8 cm

FT4 Flash Lidars meet or exceed the performance goals

EXAMPLE FLASH LIDAR IMAGE

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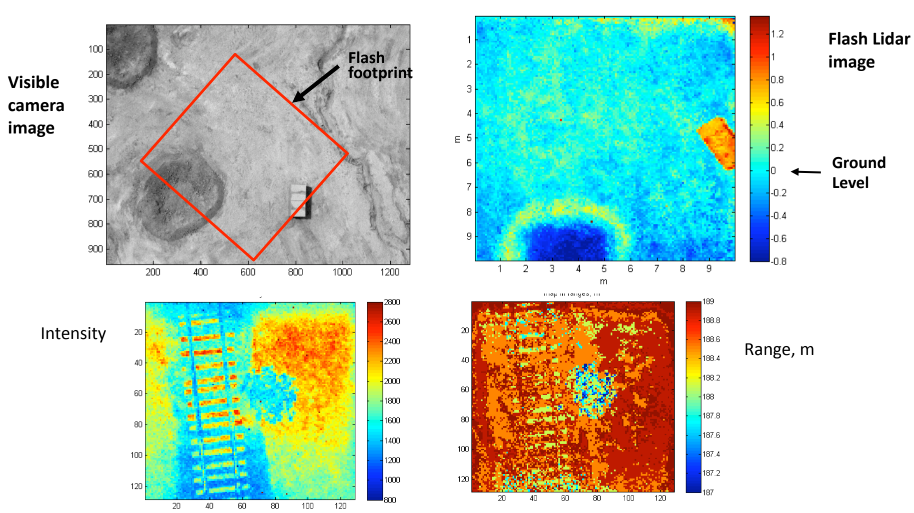
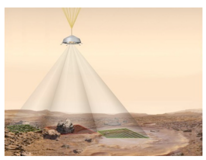
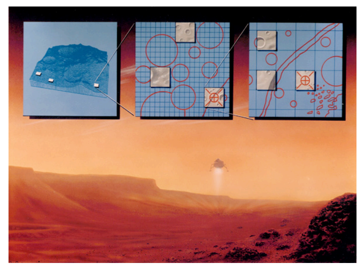


Hazard Detection and Avoidance

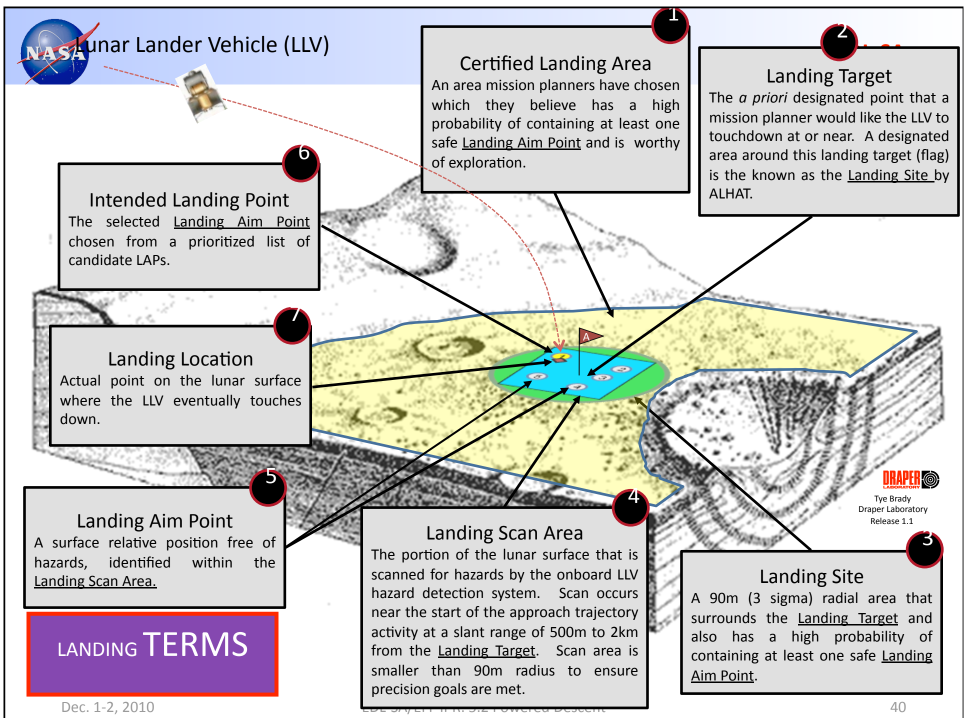
EDL-SA

- **Mars safe landing is accomplished through:**
  - **Pre-mission terrain mapping and characterization**
  - **Landing site selection**
  - **Vehicle soft landing system**
- **Addition of Hazard Detection and Avoidance capability would increase the areas of Mars where safe landing could be achieved**
  - **Allows real-time sensing of hazards smaller than can be identified *a priori***
  - **HDA sensor can be designed to provide the resolution needed to determine safe site given the mission design (vehicle capability, landing site, environment, trajectory)**
- **Lunar HDA development work maps well to Mars EDL**
  - **Flash lidar**
  - **HDA algorithms**
  - **Powered descent guidance**





Lunar Lander Vehicle (LLV)



LANDING TERMS

LLV & Terrain Model is Important

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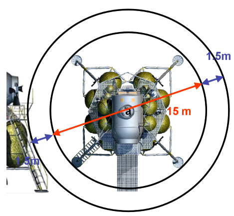
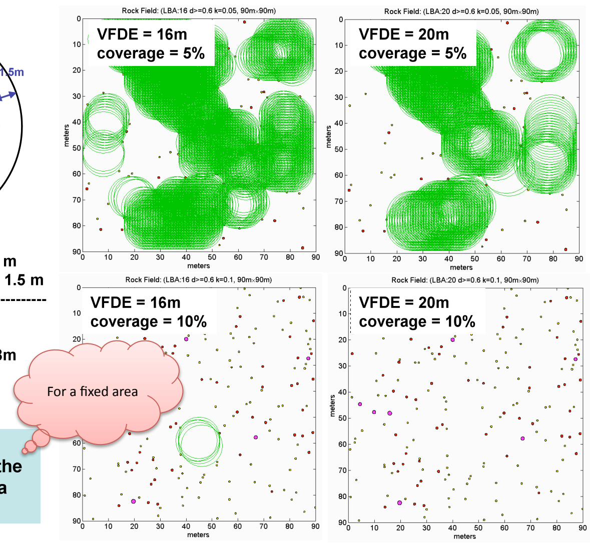
Previous Approach to Safe Landing Analysis Focused on Rocks



LLV diameter: 15 m
GNC Error: +/- 1.5 m

Vehicle Footprint Dispersion Ellipse (VFDE) 18m



As VFDE and rock abundance increase, the probability of finding a safe site decreases.

JOHNSON, A., et. al, JPL TIM, April 2008.

Safe Landing

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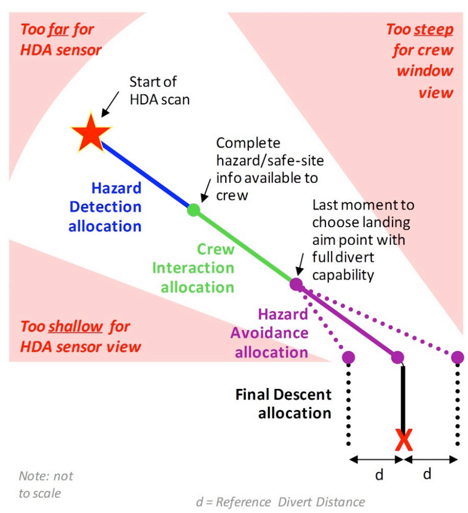
ALHAT trade studies underway…

- **HDA sensor hardware/ algorithm options**
- **Balance the needs of**
  - ***Hazard detection***
  - ***Crew interaction***
  - ***Crew visibility***
  - ***Hazard avoidance***



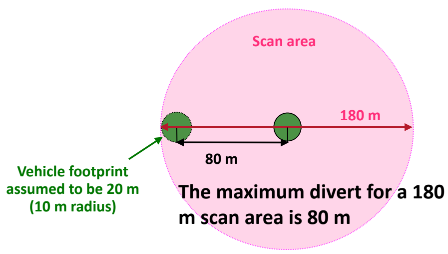
PASCHALL, S., BRADY, T., COHANIM, B, SOSTARIC, R.., "A Self Contained Method for Safe and Precise Lunar Landing", IEEE Aerospace Conference, Big Sky, Montana, 1 – 8 March 2008.

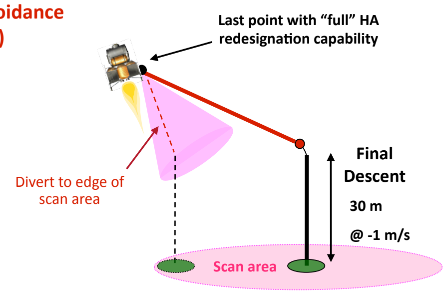
Hazard Avoidance

EDL-SA

- **Hazards must be detected early enough that they can be avoided**
  - **for a reasonable amount of propellant and**
  - **without exceeding tipover limits or other vehicle constraints**
- **The required divert distance capability can be sized by relating it to the size of the hazard scan area**
  - **The hazard scan area is determined by a probalistic terrain analysis to determine the amount of area needed to ensure a safe landing**
- **The required divert distance drives the point at which divert must be initiated**

Hazard Avoidance
(HA)

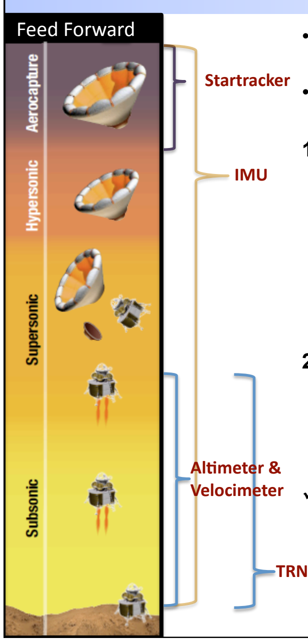




5.3 ALHAT Navigation Performance

Jody L. Davis
Jeremy Shidner

Overview



- Objective: To assess initial navigation performance of 6DOF entry Monte Carlos using EFF simulation
- Compared *two* Monte Carlos to evaluate ALHAT navigation filter functionality:

1) 2000-case 6DOF entry (3DOF descent) Monte Carlo simulation w/ ALHAT navigation filter, Apollo guidance and LQR bank angle controller
   - No TRN
   - Startracker off at entry interface
   - Altimeter measurements start at engine ignition (6km altitude)
   - Velocimeter measurements start at 2km altitude (based on ALHAT velocimeter)
2) Same Monte Carlo generated as 1) but w/ simple propagator navigation reducing navigation error manually during SRP to mimic TRN updates of an ideal ALHAT system
   - Three ”mock”- TRN measurements at 5km, 2km & 1km altitudes

✓ Initial results show good navigation performance using SRP (w/ altimetry & velocimetry) and initial TRN comparison during descent to reduce navigation position error for precision landing

Monte Carlo Inputs

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- Usual aerodynamic, atmospheric and vehicle dispersions included
- Navigation & sensor-specific Monte Carlo inputs
  - Sensor errors taken from ALHAT project sensor specification documentation
  - Conservative initial Nav state errors

Parameter		Mean	Units		Dispersion Max/Min	3-sigma	Units	Type
Sensors								
Accelerometer	bias	0	m/s^2	+/-		8.250E-04	m/s^2	Gaussian
(same error for each direction)	scale factor	0	%	+/-		4.500E-04	%	Gaussian
	random noise		m/s^2	+/-		9.000E-05	m/s^2	Gaussian
Gyro	bias	0	rad/s	+/-		1.745E-07	rad/s	Gaussian
(same error for each direction)	scale factor	0	%	+/-		2.700E-05	%	Gaussian
	random noise		rad/s	+/-		1.309E-07	rad/s	Gaussian
Startracker	bias	0	deg	+/-		0.01667	deg	Gaussian
(same error for each direction)	random noise	0	deg	+/-		0.04167	deg	Gaussian
Altimeter *	bias	0	m	+/-		0.0	m	Gaussian
	scale factor	0	%	+/-		0.0	%	Gaussian
				+/-				
	random noise		m	+/-		15.000	m	Gaussian
Velocimeter (lo-fi) *	bias	0	m/s	+/-		0.003	m/s	Gaussian
	scale factor	0	%	+/-		0.000	%	Gaussian
	random noise		m/s	+/-		0.018	m/s	Gaussian
TRN *	bias	0	m/s	+/-		15.000	m	Gaussian
				+/-		24.7 (12–15km)		
				+/-		0.3225% alt – 14.025 (7–12 km)		
TRN	random noise		m	+/-		8.55 (5–7 km)	m	Gaussian
Initial States				+/-				
	inertial position			+/-		2.0 (xi)		
	error			+/-		2.0 (yi)		
				+/-		2.0 (zi)		
NAV States			km	+/-			km	Gaussian
	inertial velocity			+/-		2.0 (vxi)		
	error			+/-		2.0 (vyi)		
				+/-		2.0 (vzi)		
			m/s	+/-			m/s	Gaussian
	attitude error		deg	+/-		0.04	deg	Gaussian

****** Monte Carlo run with no altimeter/velocimeter error since ALHAT navigation filter process noise needs to be re-tuned. Also, TRN updates in filter not included.*

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ALHAT Navigation Monte Carlo Results (No TRN)

Entry Interface

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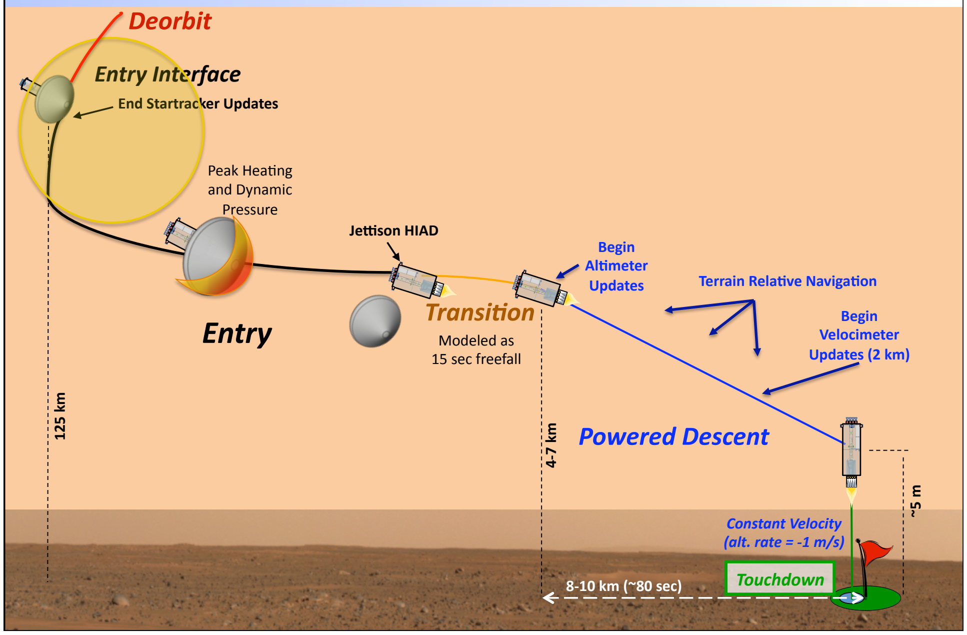
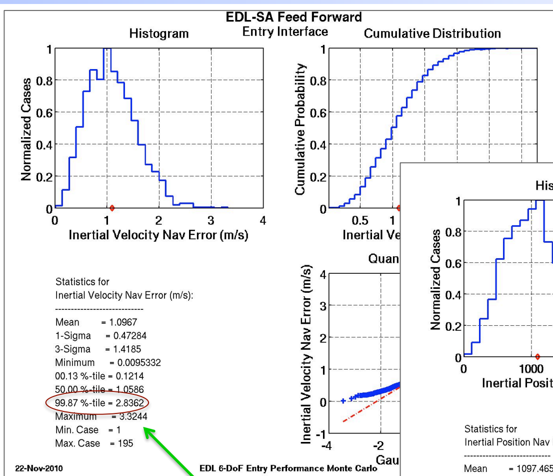


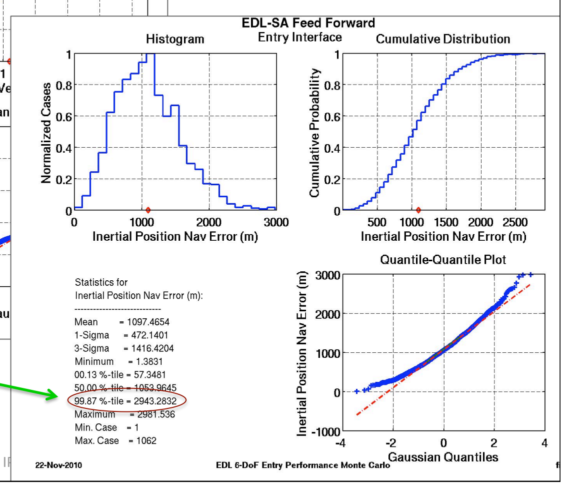
Initial ALHAT Nav Monte Carlo Results

Entry Interface

EDL-SA

Initial (deorbit) position Nav error of 3.5 km & velocity Nav error of 3.5 m/s (3-sigma)

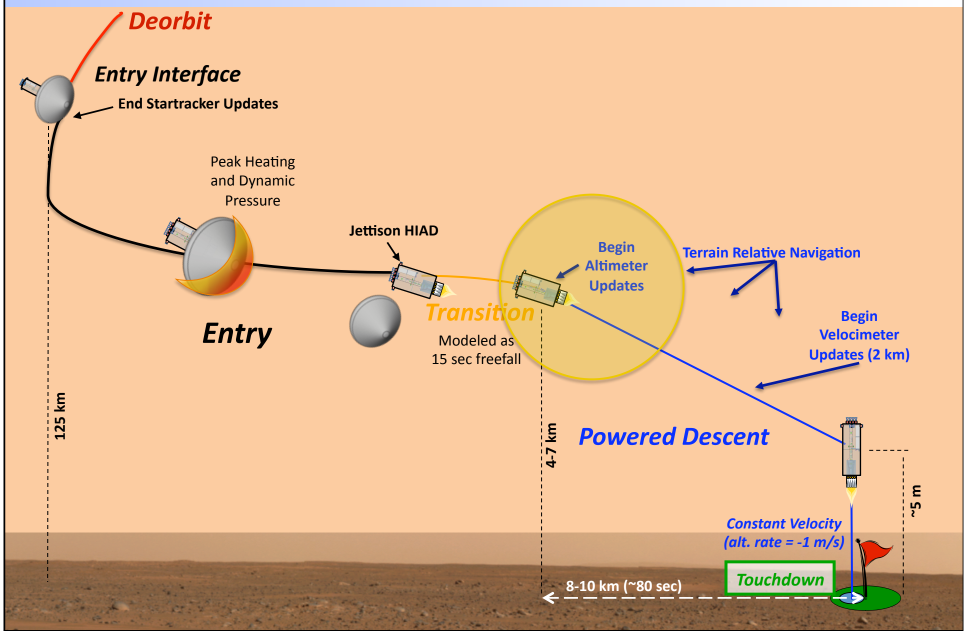




Entry position Nav error of 3 km & velocity Nav error of 3 m/s (3-sigma)

Altimetry Updates

EDL-SA

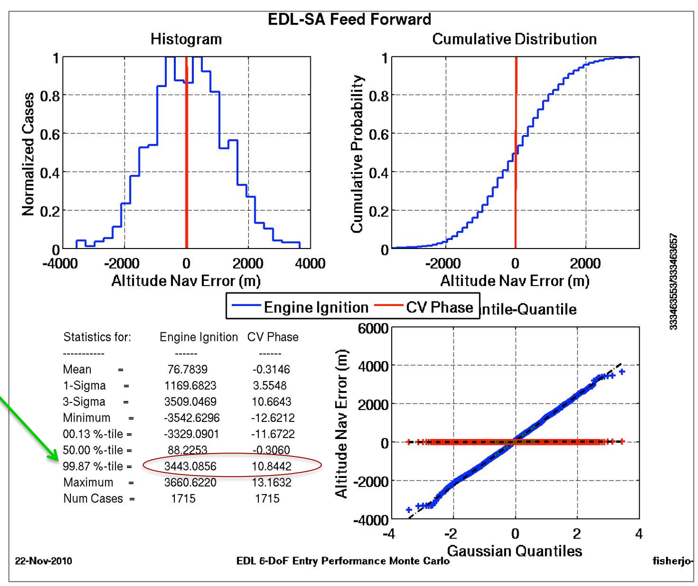


Initial ALHAT Nav Monte Carlo Results

Powered Descent

EDL-SA

Altitude Nav error is squashed after altimeter updates starting at engine ignition, 3.4 km (44% error) down to 11 m (1% error) (3-sigma)



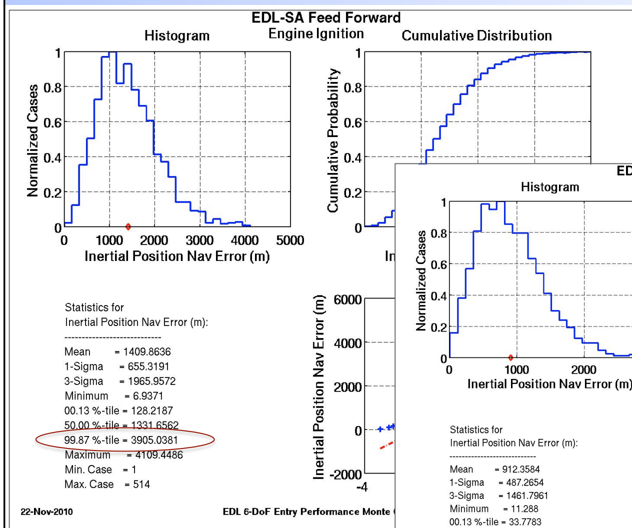
Statistics for:	Engine Ignition	CV Phase
-----------	------	------
Mean =	76.7839	-0.3146
1-Sigma =	1169.6823	3.5548
3-Sigma =	3509.0469	10.6643
Minimum =	-3542.6296	-12.6212
00.13 %-tile =	-3329.0901	-11.6722
50.00 %-tile =	88.2253	-0.3060
99.87 %-tile =	3443.0856	10.8442
Maximum =	3660.6220	13.1632
Num Cases =	1715	1715

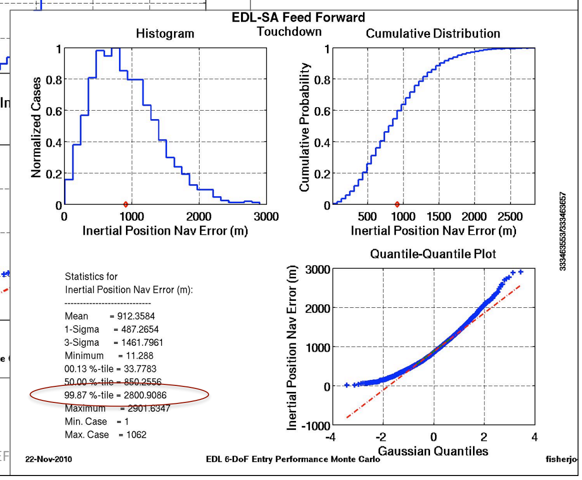
Initial ALHAT Nav Monte Carlo Results

Powered Descent

EDL-SA

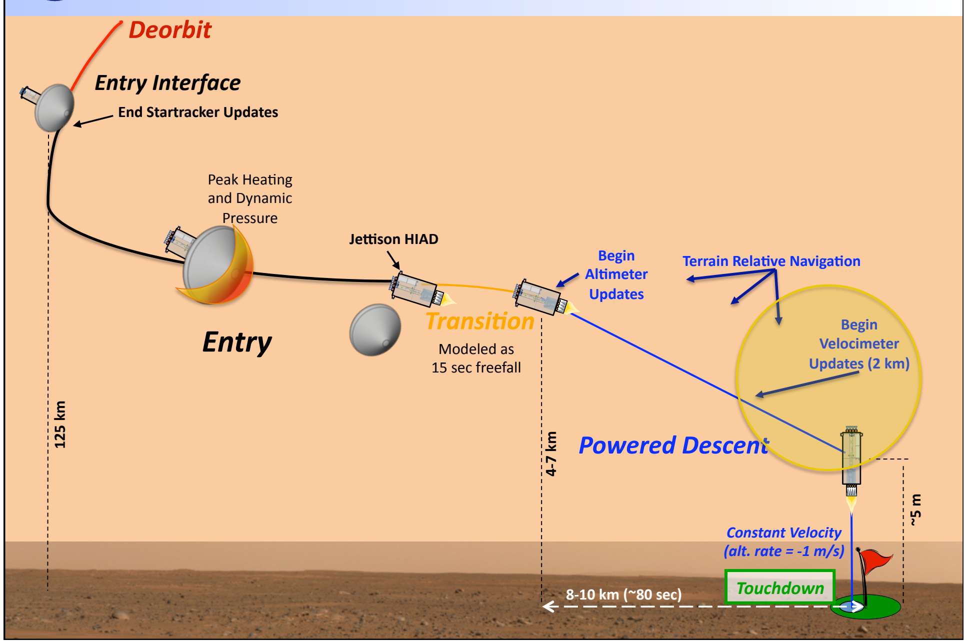
Improvement in position Nav error is seen after altimeter updates, from 4 km to 2.8 km (3-sigma)





Velocimetry Updates

EDL-SA

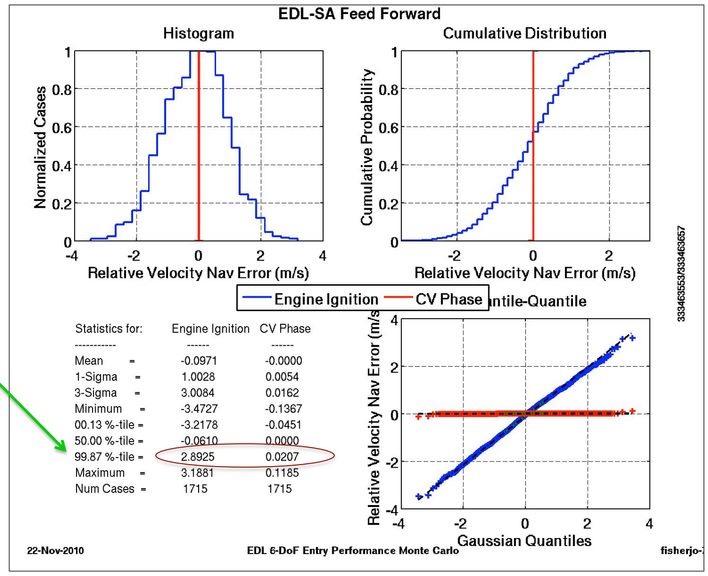


Initial ALHAT Nav Monte Carlo Results

Powered Descent

EDL-SA

Relative velocity Nav error is squashed after velocimeter updates starting at engine ignition, 3 m/s (1% error) down to 2 cm/s (0.01% error) (3-sigma)

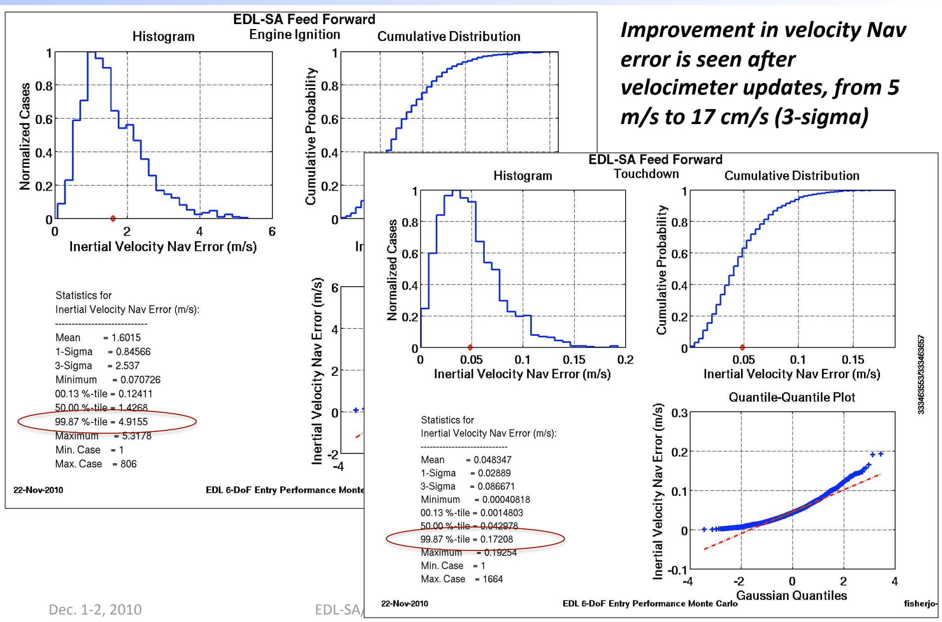


Initial ALHAT Nav Monte Carlo Results

Powered Descent

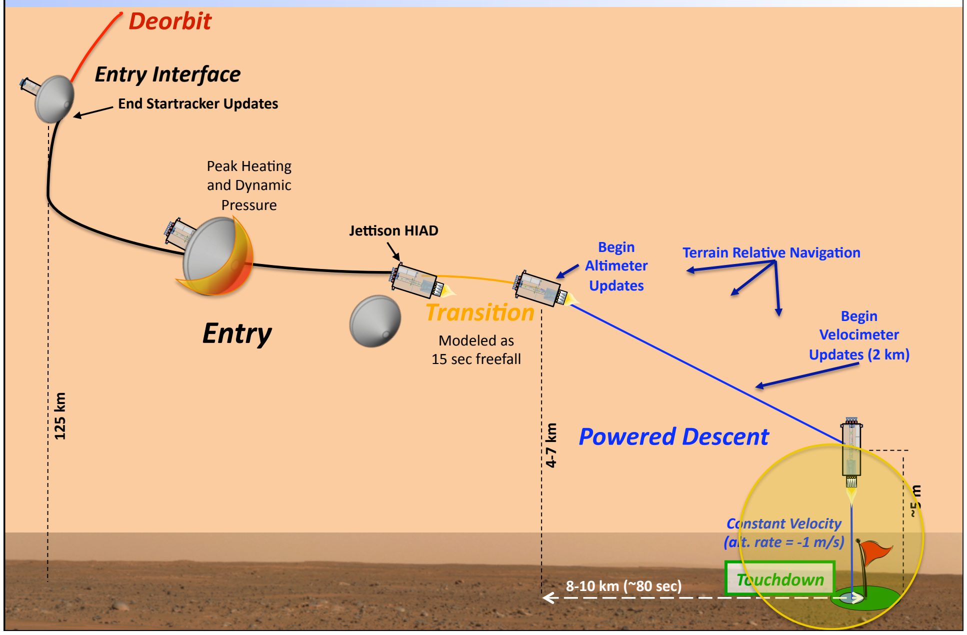
EDL-SA

Improvement in velocity Nav error is seen after velocimeter updates, from 5 m/s to 17 cm/s (3-sigma)



Touchdown

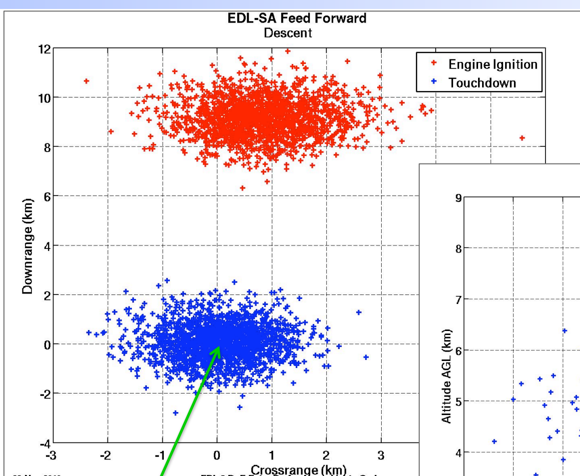
EDL-SA



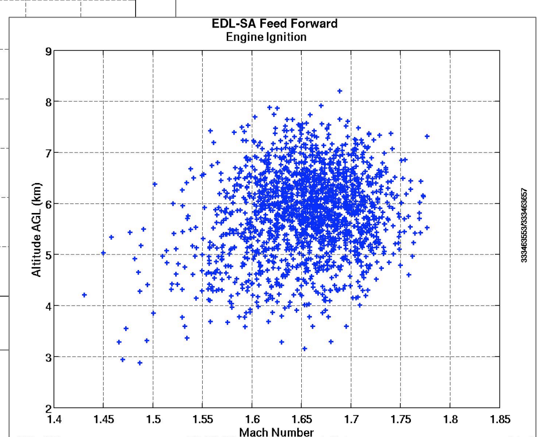
Initial ALHAT Nav Monte Carlo Results

Powered Descent

EDL-SA



More improvement in position Nav error is needed to reduce touchdown footprint

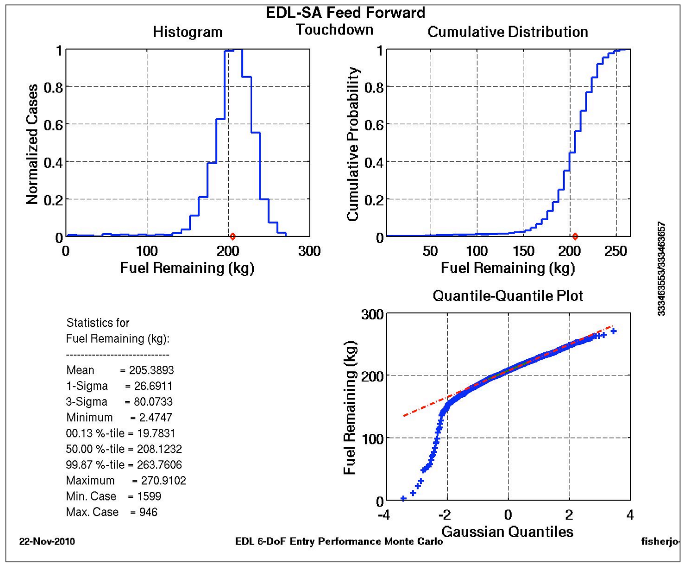


Using navigation updates & SRP can get within 2.4 km of the landing target (3-sigma)

Initial ALHAT Nav Monte Carlo Results
Touchdown

EDL-SA

Fuel remaining at touchdown is primarily similar to powered descent study results with perfect navigation



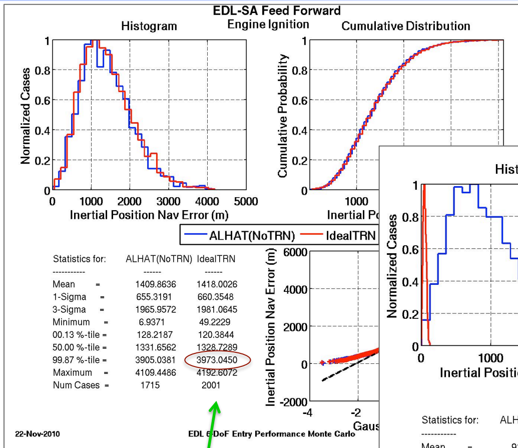
EDL-SA

No TRN vs. "Mock"-TRN (Ideal ALHAT) Monte Carlo Results

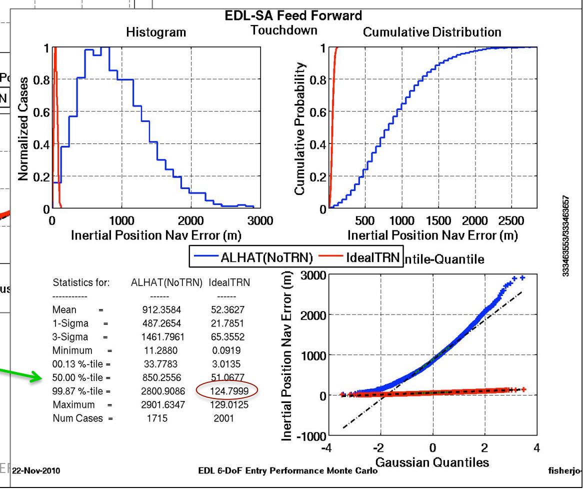
No TRN vs. TRN Monte Carlo Comparison EDL-SA

Navigation Error Reduction

Ideal TRN case: ***three TRN updates mimicked as position Nav error reductions down to 85 m during SRP***



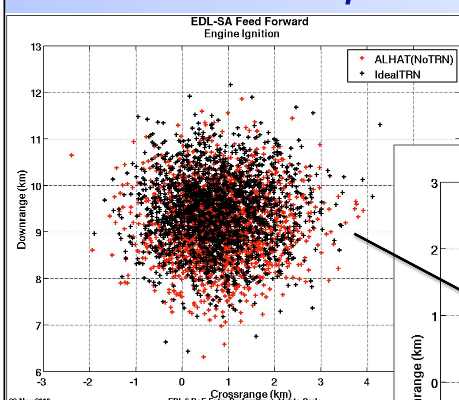
Position Nav error reduced from 4 km to 125 m (3-sigma) at touchdown

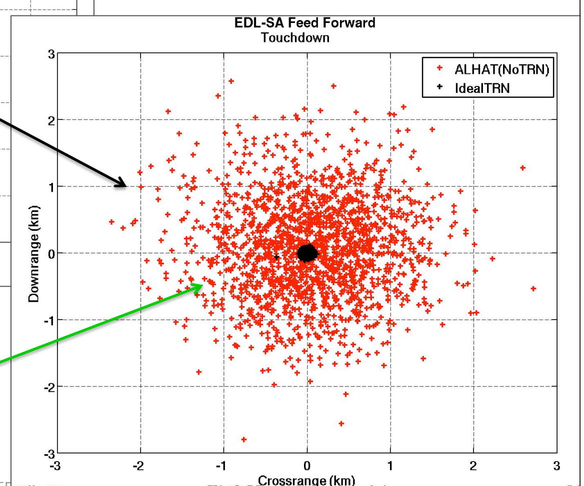


No TRN vs. TRN Monte Carlo Comparison EDL-SA

Footprint Size Reduction

Improvement in position Nav error in form of TRN updates shown here are needed to reduce touchdown footprint





TRN updates are needed to get within 100 m of the landing target (3-sigma)

Summary

EDL-SA

- 6DOF entry Monte Carlos w/ 3DOF descent shown initially assess ALHAT navigation filter (as-delivered) performance
- ALHAT navigation filter successfully utilizes startracker, altimeter and velocimeter (w/o error) measurements
  - Navigation error in altitude and velocity during SRP phase are greatly reduced
  - Still an issue with noisy measurements, filter needs tuning
  - Need TRN update capability in ALHAT filter
- Initial results show good navigation performance using SRP (with altimetry/velocimetry) and initial TRN comparison during descent to reduce navigation position error for precision landing
  - Altimetry/velocimetry updates & SRP can get within 2.4 km of the landing target (3-sigma)
  - Need TRN (or beacon or similar sensor) to get landing accuracy down to 100 m (3-sigma) or less

Backup

Monte Carlo Inputs

EDL-SA

```
//*********** AC & EDL Monte Carlo Inputs ************
// ------------------------
//  Initial State
// ------------------------
ac_gamei  -11.8063      +/- 0.25         normal
ac_hypvel  5463.59222    +/- 20.0         normal
ac_bpang   270.0          +/- 0.10        normal
ac_tof   -30.0            +/- 2.0      normal
edl_malta   500         +/- 0.0   normal
edl_maltp  -219.017015  +/- 0.0   normal
edl_inc     90          +/- 0.0   normal
edl_lan     3.33691322735950337e+02          +/- 0.1   normal
edl_argp    4.44004987171960863e+01          +/- 0.1   normal
edl_lan_disp  0.0       +/- 0.1   normal
edl_argp_disp 0.0       +/- 0.1   normal
edl_truan   180         +/- 0.0   normal

// --------------------------------------
//  Initial Attitude/Rate Uncertainties
// --------------------------------------
ac_alpha          -18.0          +/- 0.25       normal
ac_beta           0.0            +/- 0.25       normal
ac_bnkang         0.0            +/- 0.25       normal
ac_rolbd          0.0            +/- 0.10       normal
ac_pitbd          0.0            +/- 0.10       normal
ac_yawbd          0.0            +/- 0.10       normal
edl_alpha         -18.0          +/- 0.25       normal
edl_beta          0.0            +/- 0.25       normal
edl_bnkang        0.0            +/- 0.25       normal
edl_rolbd         0.0            +/- 0.10       normal
edl_pitbd         0.0            +/- 0.10       normal
edl_yawbd         0.0            +/- 0.10       normal

// --------------------------------------
//  Atmospheric Uncertainties
// --------------------------------------
atm_rnd_num     1             1:29999        integer
tau             0.45          0.1:0.9        uniform
denkt           1.0           +/-15%         uniform
perts           0             1:1            uniform


// --------------------------------------
//  Aerodynamic Uncertainties
// --------------------------------------
ca_mult         1.0           0.90:1.1       normal
cn_mult         1.0           0.90:1.1       normal
cy_mult         1.0           0.90:1.1       normal
edl_alpha_add   0.0           +/- 1.0        normal

// --------------------------------------
//  Mass Property Uncertainties
// --------------------------------------
ac_xcgbias_ldp25  -0.22486       +/- 0.001      normal
ac_ycgbias_ldp25   0.0           +/- 0.001      normal
ac_zcgbias_ldp25   0.462         +/- 0.001      normal
ac_xcgbias_ldp1    -0.22486       +/- 0.001      normal
ac_ycgbias_ldp1     0.0           +/- 0.001      normal
ac_zcgbias_ldp1     0.175         +/- 0.001      normal
edl_xcgbias    -2.5145        +/- 0.001       normal
edl_ycgbias     0.0           +/- 0.001       normal
edl_zcgbias     0.2512        +/- 0.001       normal

// --------------------------------------
//  ALHAT IMU Uncertainties
// --------------------------------------
bias_acc_x      0             +/- 8.250E-04   normal
bias_acc_y      0             +/- 8.250E-04   normal
bias_acc_z      0             +/- 8.250E-04   normal
sf_acc_x        0             +/- 4.500E-04   normal
sf_acc_y        0             +/- 4.500E-04   normal
sf_acc_z        0             +/- 4.500E-04   normal
iseed_acc_x     1             1:29999         integer
iseed_acc_y     1             1:29999         integer
iseed_acc_z     1             1:29999         integer
rnoise_acc      0.0           9.0E-05:9.0E-05 uniform

bias_gyro_x     0             +/- 1.745E-07   normal
bias_gyro_y     0             +/- 1.745E-07   normal
bias_gyro_z     0             +/- 1.745E-07   normal
sf_gyro_x       0             +/- 2.700E-05   normal
sf_gyro_y       0             +/- 2.700E-05   normal
sf_gyro_z       0             +/- 2.700E-05   normal
iseed_gyro_x    1             1:29999         integer
iseed_gyro_y    1             1:29999         integer
iseed_gyro_z    1             1:29999         integer
rnoise_gyro     0.0           1.309E-07:1.309E-07     uniform

// --------------------------------------
//  ALHAT Star Camera Uncertainties
// --------------------------------------
iseed_st_x        1           1:29999        integer
iseed_st_y        1           1:29999        integer
iseed_st_z        1           1:29999        integer
bias_st_x       0.0      +/- 0.0               normal      # 3-sig, deg
bias_st_y       0.0      +/- 0.0              normal      # 3-sig, deg
bias_st_z       0.0      +/- 0.0              normal      # 3-sig, deg
rnoise_st       0.0         0.0:0.0        uniform

// --------------------------------------
//  ALHAT Altimeter Uncertainties
// --------------------------------------
iseed_alt          1           1:29999        integer
rnoise_alt         0.0         0.0:0.0       uniform

// --------------------------------------
//  ALHAT Velocimeter Uncertainties
// --------------------------------------
iseed_vel_horz     1           1:29999         integer
iseed_vel_vert     1           1:29999        integer
rnoise_vel_horz   0.0          0.0:0.0        normal
rnoise_vel_vert   0.0          0.0:0.0        normal

// --------------------------------------
//  Knowledge Uncertainties
// --------------------------------------
ac_xi_delta       0              +/- 2000       normal
ac_yi_delta       0              +/- 2000       normal
ac_zi_delta       0              +/- 2000       normal
ac_vxi_delta      0              +/- 2          normal
ac_vyi_delta      0              +/- 2          normal
ac_vzi_delta      0              +/- 2          normal
ac_ex             0.0            +/- 1.0        normal
ac_ey             0.0            +/- 1.0        normal
ac_ez             0.0            +/- 1.0        normal
ac_att_err_mag    0.0            0.0:1.0        uniform
edl_xi_delta      0              +/- 2000       normal
edl_yi_delta      0              +/- 2000       normal
edl_zi_delta      0              +/- 2000       normal
edl_vxi_delta     0              +/- 2          normal
edl_vyi_delta     0              +/- 2          normal
edl_vzi_delta     0              +/- 2          normal
edl_ex            0.0            +/- 0.1        normal
edl_ey            0.0            +/- 0.1        normal
edl_ez            0.0            +/- 0.1        normal
edl_att_err_mag   0.0            0.0:0.1        uniform
```


Initial ALHAT Nav Monte Carlo Results

Entry

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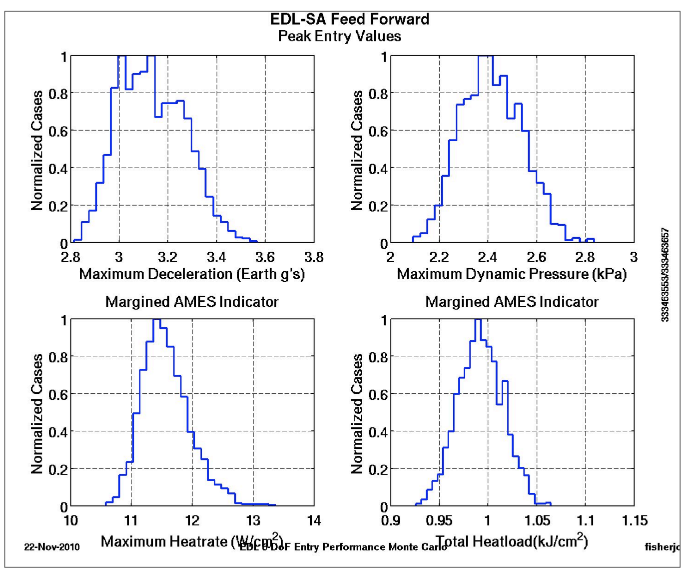
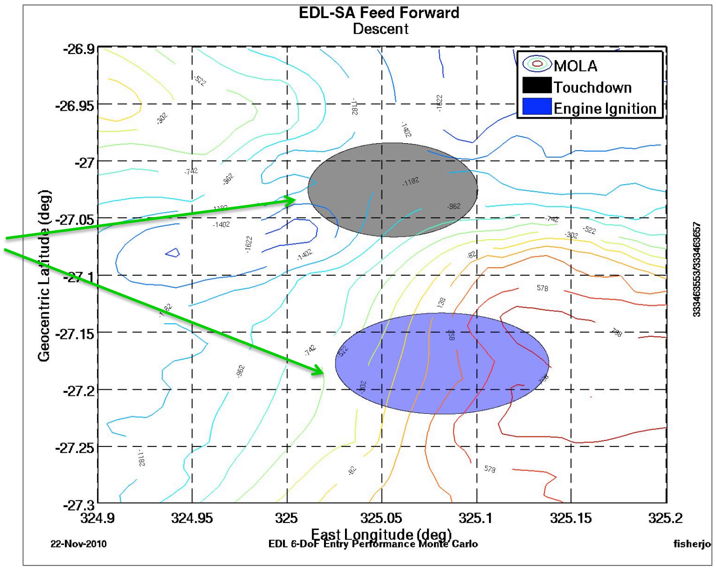


Initial ALHAT Nav Monte Carlo Results

EDL-SA

Powered Descent

Using navigation updates during SRP slightly reduces footprint from engine ignition to touchdown



No TRN vs. TRN Monte Carlo Comparison

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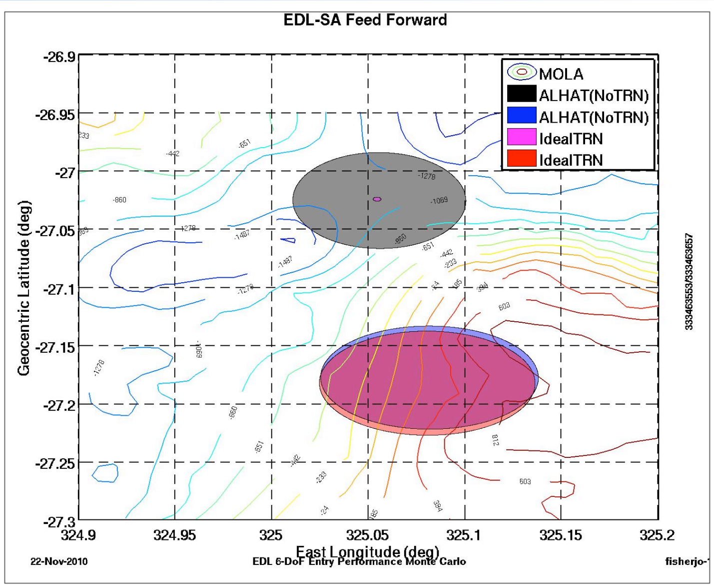
Footprint Size Reduction



5.4 ALHAT Assessment: Summary, Recommendations, and Future Work

Ron Sostaric
Jody Davis

Summary

- Integrated ALHAT navigation filter (no TRN) into simulation
- Showed entry guidance, powered descent guidance, and navigation performance
- Provided flight conditions for SRP
- Provided flight conditions for TRN during powered descent and showed initial feasibility
- Provided flight conditions for HDA and showed initial feasibility
- Showed initial integrated GNC system performance for EDL

Recommendations

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- Pursue further examination towards use of ALHAT-developed sensors for Mars EDL applications
  - Laser altimeter – altimetry, TRN
  - Doppler lidar velocimeter – offers significant performance improvement over state of the art (MSL terminal descent radar)
  - Flash lidar – TRN, HDA
- Continue to pursue the use of Terrain Relative Navigation (TRN) for Mars EDL
  - Include passive optical in addition to active methods mentioned above
- Continue to work to adapt Hazard Detection and Avoidance (HDA) for Mars landings

Future Work

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- Update current baseline navigation and integrated GNC performance with latest filter and sensor models
- Update ALHAT sensor models and operating ranges for Mars
- Update Star tracker operating range and conditions
- GNC performance sensitivity to measurement quality and availability
- Early TRN Study
  - Trade timing, number of TRN measurements. Consider feasibility of performing TRN prior to Powered Descent.
- Perform divert sensitivity study
- Perform detailed HDA analysis for Mars landing
  - Consider terrain, landing footprint size including GNC errors, lidar performance, and other factors

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6.0 Parametric Mass Modeling Objective and Overview

Jamshid A. Samareh

Mass Modeling Session

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- **Describe the mass modeling process**
- **Describe the basis for HIADs, SRP, and TPS**
- **Show sample results**

13:00	13:15	0:15	**6.0**	**Mass Modeling Assessment Objectives and Overview**	*Samareh*	Review motivation and objectives of this section and identify major components of the design, will include details about the payload
13:15	13:45	0:30	6.1	EFF Mass Model Development	*Samareh*	
13:45	14:15	0:30	6.2	Mass Optimization Process	Olds	Trajectory description, explain outliers
			6.3	Component mass models		
14:15	14:45	0:30	6.3.1	Descent Stage	*Komar*	
14:45	**15:00**	**0:15**		***BREAK***		
15:00	15:30	0:30	6.3.2	Ablator TPS	*Kinney/ McGuire*	Focus on facts about how the model was developed and assumptions made
15:30	16:00	0:30	6.3.3	Insulator TPS	*Del Corso/ Cheatwood*	Focus on facts about how the model was developed and assumptions made
16:00	16:30	0:30	6.4	Recommendations/Lessons Learned/Future Work	*Samareh*	

Architectures

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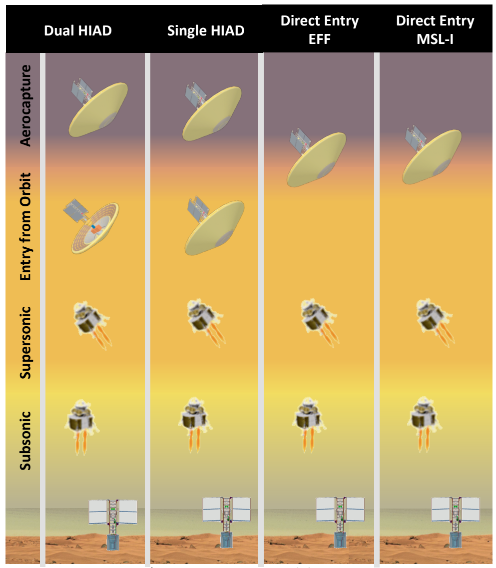

Major Mass Model Components

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- Components
  - Payload 2+ mT
  - HIAD (based on EDL-SA exploration architectures)
  - Engines (EXAMINE)
  - Flexible TPS (ablator and/or insulator)
  - Misc (similar to exploration architecture: rigid section, payload adaptor, separation mechanism, …)
- Margin of 49.5% applied across all mass components (except payload)
- Parametric Mass Model
  - Mass models are function of shape and simulation parameters
  - E.g., TPS mass = function(shape, heat load)

Process for Mass Model Development

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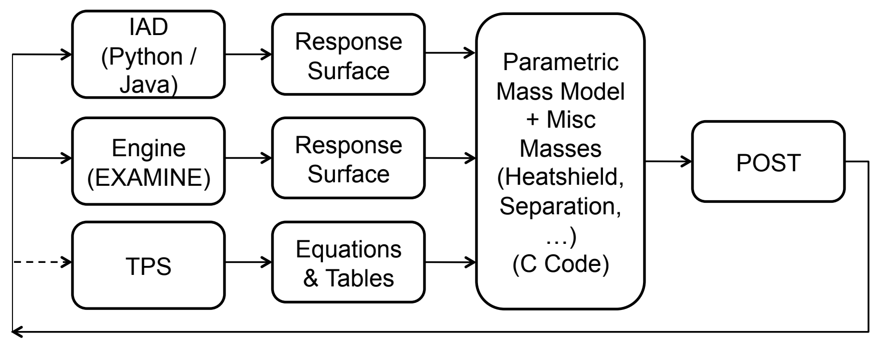

6.1 EFF Parametric Mass Modeling Development

Jamshid A. Samareh

Outline

- Candidate Payload
- Packaging
- HIAD model
- TPS Diameter Sweep Trade
- Proposed Model Improvements

Candidate Payload

Movable Fission Power System (MFPS)

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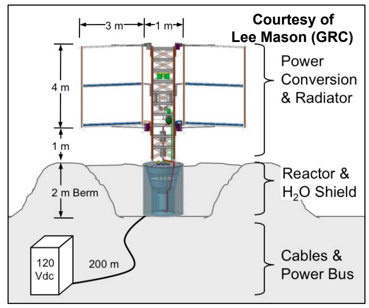
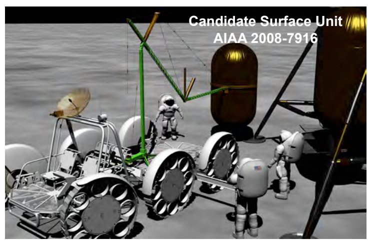
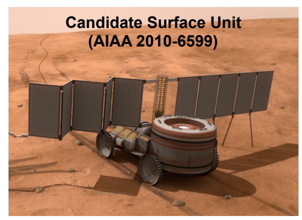
Movable FPS Subsystem	Mass (kg)	Includes:
Power Plant, 10 kWe Fission Surface Power (FSP), (3x1.5x7 m), 8-year design life	1615	Reactor, water shield vessel, power conversion, radiator, and truss/ structure.
Power Management & Distribution (PMAD): transmission cable (<1m dia, 240 kg) + load bus to interface to the mission power loads (1x1x1 m, 175 kg)	415	Cabling, electrical controls, and 120 Vdc load interface bus.
Water (for Shield)	1310	Liquid water for filling shield vessel prior to reactor startup.
Total Current Best Estimate	3340	







Packaging (Dual HIAD)

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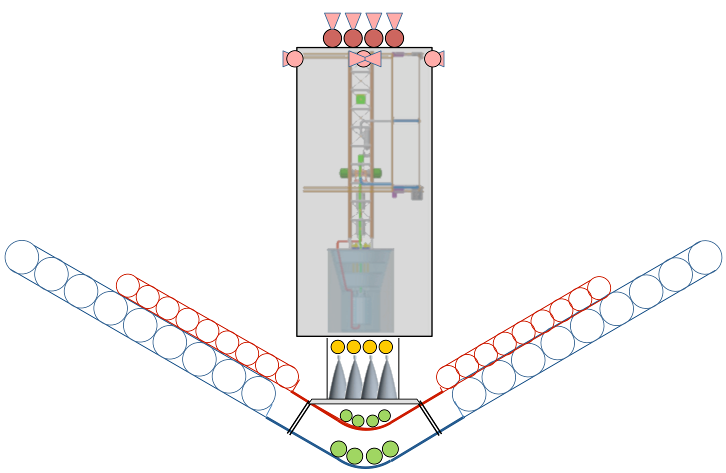

Packaging (Dual HIAD), Cont.

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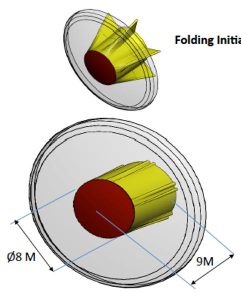
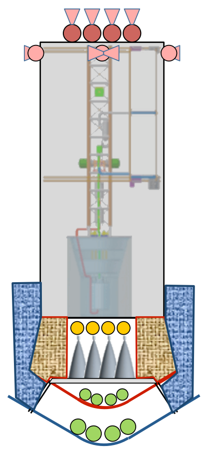
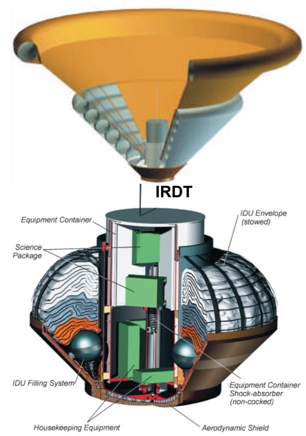
Candidate Packaging Concept for Ablative TPS (NASA/TM-2010-216720)







Packaging, Conti.

(Source: Delta IV Payload Planners Guide)

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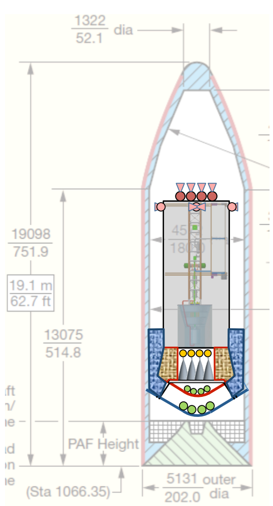
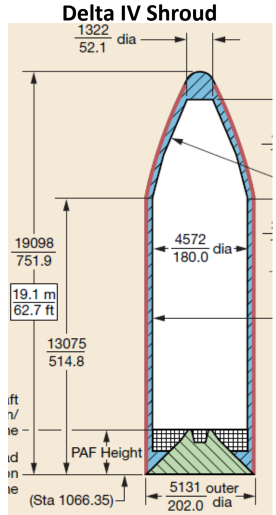


Delta IV Shroud



HIAD Model

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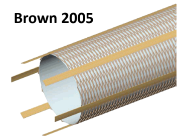
Brown 2005



- Current HIAD model is primary based on the work of Brown (Vertigo) and Rohrschneider (Ball)
- Why fiber reinforced concept?
  - 12× advantage in specific strength of fiber compared to film (AIAA-2007-2543)
  - Fiber reinforced is lighter than film and has higher bending stiffness. 5 MT payload will have a mass fraction of approximately 5% for fiber reinforcement film, and 16% for film strength alone (AIAA-2007-2543).
- MER is function of diameter, drag coefficient, dynamic pressure, heatshield diameter, half-cone angle, …
  - MER results are within 6% of MIAS 60/70 mT (excluding TPS).

2.5 m Stacked Tori Manufacturing Demonstration (Vertigo)

HIAD Model, Cont.
(HIAD Elements)

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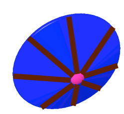
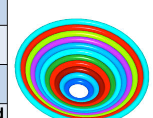
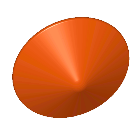
Components	Role	Materials for HIAD	Notes
Radial straps	Tie tori to together and to rigid shell, carry radial loads	Kevlar-49	Alternatives: other para-aramids [Technora & Twaron] and Vectran
Gores	Carry circumferential loads	Upilex	Alternatives: other polyimide films [Kapton, Teflon AF, Apical, Peek (polyetheretherketone)]
Torus, fiber reinforcement	Hoop stress	Kevlar-49	Alternatives: other para-aramids [Technora & Twaron] and Vectran
Torus, axial straps	Buckling loads	Kevlar-49	Alternatives: other para-aramids [Technora & Twaron] and Vectran
Torus, gas barrier	Retain gas	Upilex	Alternatives: coating, Silicone film, thermoplastic & nylon film
Torus, gas	For compression wrinkling	Hydrazine product	Alternative: air bag gas generator, and compressed gas
Payload adapter	Link between aeroshell and payload		1% of entry mass
Rigid heatshield structure	Spherical cap center part		6 kg/m2 (close to MSL backshell)
TPS	Heat load	Ablator & Insulator	MER based on total heat loads
Separation Mechanism	Separate aeroshell from payload & engine	Metallic	Vertical rails and circumferential beams with wheels







HIAD Model, Cont.
(Design Factor of Safety, DFS)

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Design Factor of Safety (DFS) for Soft Goods. Source: Structural Design and Test Factors of Safety for Spaceflight Hardware (NASA-STD-5001A, 08-05-2008)

Limit Load: The maximum anticipated load, or combination of loads that a structure may experience during its service life under all expected conditions of operation or use.

Ultimate Design Load: The product of the ultimate factor of safety and the limit load.

"…..the criteria in this document are to be considered as minimum acceptable values unless adequate engineering risk assessment is provided which justifies the use of lower values."

Table 1—Minimum Design and Test Factors for Metallic Structures

Verification Approach	Ultimate Design Factor	Yield Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
Prototype	1.4	1.0*	1.4	NA or 1.05**
Protoflight	1.4	1.25	NA	1.2***

NOTES:
* Structure must be assessed to prevent detrimental yielding during flight, acceptance, or proof testing.
** Propellant tanks and SRM cases only.
*** Protoflight level testing is required for the first article of a multiple article build. A workmanship level test is required for all subsequent copies of the first article. The workmanship test shall be approved by the responsible Technical Authority.

Table 6 – Minimum Design and Test Factors for Structural Softgoods

Hardware Criticality Classification*	Ultimate Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
1 or 2	4.0	4.0	1.2
3	2.0	2.0	1.2

*Hardware Criticality is defined in NSTS 22206, table 3.2:
1 – Loss of life or vehicle
2 – Loss of mission or next failure of any redundant item could cause loss of life/vehicle
3 –All others

HIAD Model, Cont.
Historical Values for Inflation DFS

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- **4 for airship (FAA airworthiness requirement, 881)**
- **5 for inflatable lunar habitation (Roberts 1992)**
- **4-5 for inflatable lunar habitation (Ruess et al. 2006)**
- **3 for STEM lunar habitat (Cadogan et al. 1999)**
- **5 for airlock (Cadogan et al. 98)**
- **3 for tanks and 4 for lines (Human-Robotic Hybrids for Deep-Space EVA)**
- **1.6 for Venus balloons (Izutsu 2000)**

HIAD Model, Cont.
Margins and Safety Factors

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- Load design factor of safety of 4
- Inflation
  - Gas temperature of 0° C
  - Inflation pressure margin 1.25
- Radial straps
  - Knock down DFS of 0.8 for Kevlar strength due to high temperature
- Gores
  - Seam margin of 1.05
  - Knock down DFS of 0.8 for Kevlar strength due to high temperature
- Torus
  - Knock down DFS of 0.8 for Kevlar strength due to high temperature
  - Gas barrier mass margin of 1.10

No margins included for UV and cold exposures.

HIAD Model, Conti. (FEA)

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Courtesy of Larry Prosper, Chandra Shah, and Sasan Armand

- Looked at six cases
  - 14 m HIAD
  - 8 m HIAD
  - Impact of axial straps
  - Impact of radial straps
  - Impact of dynamic and inflation pressure
  - Impact of structural topology

HIAD Model, Conti. (FEA)

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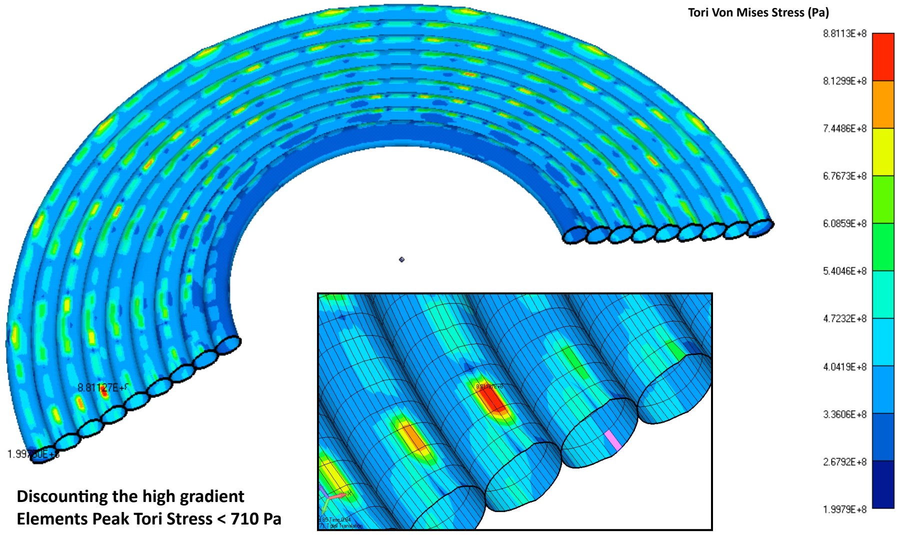
Courtesy of Larry Prosper, Chandra Shah, and Sasan Armand



Discounting the high gradient Elements Peak Tori Stress < 710 Pa

TPS Diameter Sweep Trade

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- **IRVE TPS Concept**
  - **Last version was delivered on 11/15/2010 (HIAD_Concepts_Information_JAD-v3.xlsx)**
  - **Dual HIAD, single HIAD, and two direct entries**
- **Ablator TPS Concept**
  - **Delivered on 10/25/2010 (EFF TPS MERs 10-25-2010.pdf)**
  - **Dual & single HIADs**
  - **Direct entries cases were not ready to be included for this review**

TPS Diameter Sweep Trade

EDL-SA

(Mass Optimization: Aaron Olds)

- *Goal is to maximize payload mass (2.0+ mt) for a 7.2 mt launch mass (Delta IV-H)*
- Initial T/W set to 3.7 Mars g's based on trade study results
- Discrete solutions obtained for diameters from 8 to 20 m
  - Dual HIAD scenarios
  - Single HIAD scenarios
  - Direct Entry scenarios
- Deorbit delta-V or direct entry flight path angle allowed to vary to maximize payload mass
  - Maximum entry flight path angle constrained to -0.5 deg to prevent lofting or skipping entries
  - A number of additional independent variables and constraints are involved in the optimization process to obtain a trajectory with the proper end conditions
- Reference bank control profile simulated during entry and descent
  - Bank profile modeled as a function of velocity
  - 90 deg above 2500 m/s
  - 40 deg from 2500 to 1500 m/s
  - 0 deg below 1500 m/s
  - Separation transition time of 15 sec
  - SRP powered descent modeled as modified gravity turn at 80% constant throttle
  - Constant velocity (1 m/s) phase starts 5 m altitude, touchdown at 0 km MOLA

TPS Diameter Sweep Trade

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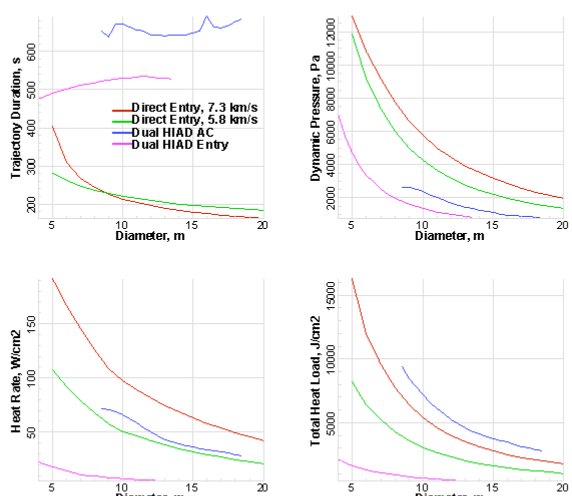
(Simulation Environments)



TPS Diameter Sweep Trade

(Dual HIAD)

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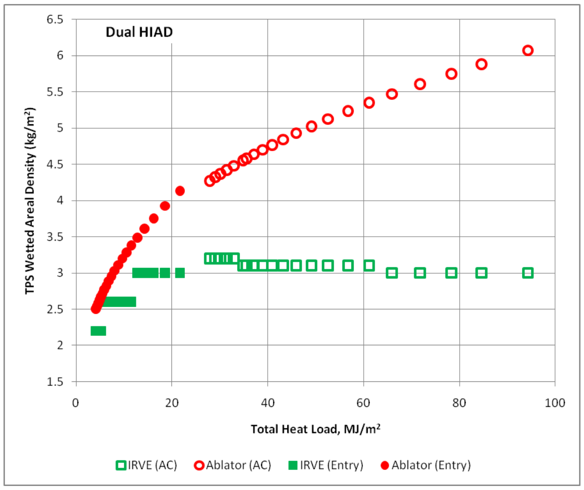
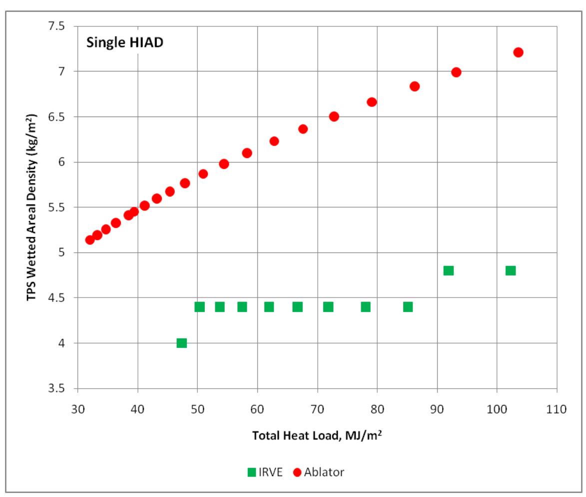


TPS Diameter Sweep Trade

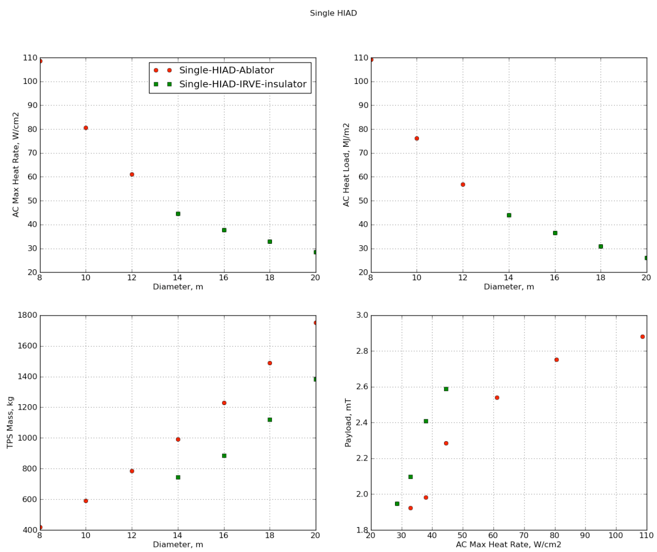
(Single HIAD)

EDL-SA



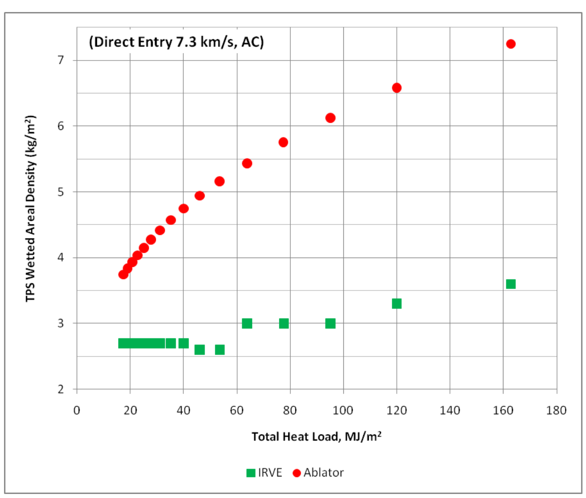
TPS Diameter Sweep Trade
(Single HIAD)

EDL-SA



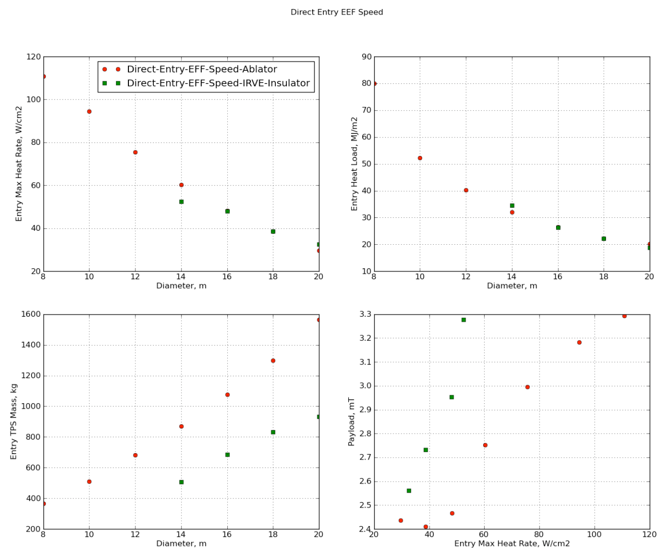
TPS Diameter Sweep Trade
(Direct Entry 7.3 km/s)

EDL-SA



TPS Diameter Sweep Trade
(Direct Entry 7.3 km/s)

EDL-SA



TPS Diameter Sweep Trade
(Direct Entry 5.8 km/s)

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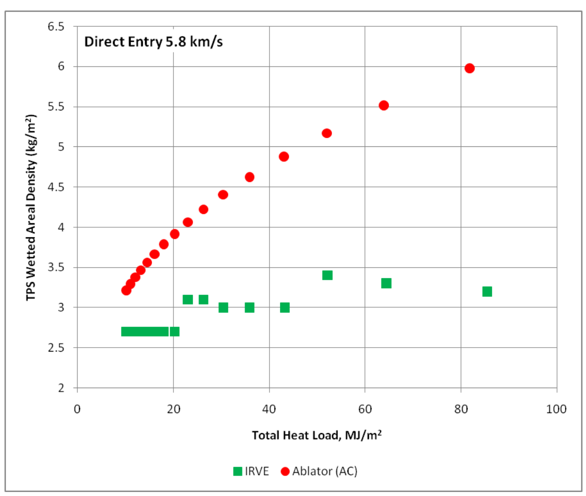

TPS Diameter Sweep Trade

(Direct Entry 5.8 km/s)

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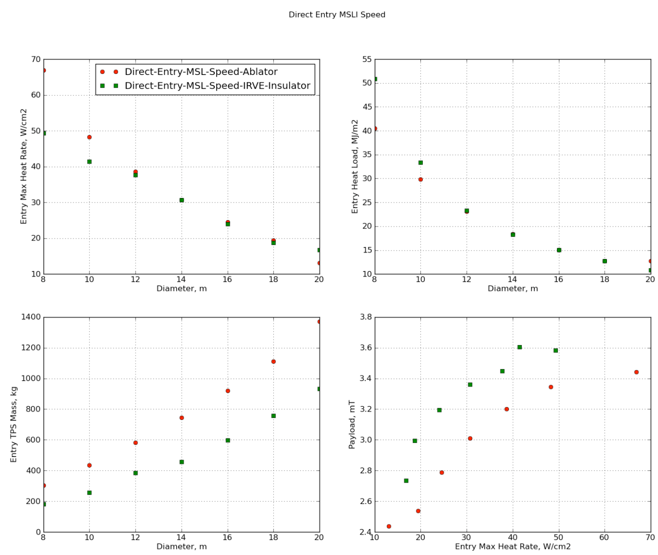

TPS Diameter Sweep Trade

(Sensitivity Analysis)

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		Ablator		Insulator	
		Nominal	Nominal + 25% Increase in TPS Areal Density	Nominal	Nominal + 25% Increase in TPS Areal Density
Dual HIAD	AC TPS Mass, kg	347	433	524	655
	Entry TPS Mass, kg	198	244	165	206
	Payload, kg	**2.63**	2.48	2.37	2.18
	Payload Reduction, %		-5.6%		-7.9%
	Payload/Launch Mass	0.36	0.34	0.33	0.30
Single HIAD	TPS Mass, kg	417	522	744	930
	Payload, kg	**2.88**	2.76	2.59	2.36
	Payload Reduction, %		-4.2%		-8.7%
	Payload/Launch Mass	0.40	0.38	0.36	0.33
Direct Entry EFF	TPS Mass, kg	367	460	685	855
	Payload, kg	**3.29**	3.19	2.95	2.76
	Payload Reduction, %		-3.2%		-6.7%
	Payload/Launch Mass	0.46	0.44	0.41	0.38
Direct Entry MSLI	TPS Mass, kg	304	380	183	230
	Payload, kg	3.44	3.35	**3.58**	3.53
	Payload Reduction, %		-2.5%		-1.4%
	Payload/Launch Mass	0.48	0.47	0.50	0.49

TPS Diameter Sweep Trade

(Summary)

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	Units		Dual HIAD		Single HIAD		Direct Entry, 7.2 km/s		Direct Entry, 5.8 km/s	
			Ablator	Insulator	Ablator	Insulator	Ablator	Insulator	Ablator	Insulator
Payload	kg		**2627**	**2371**	**2881**	**2589**	**3294**	**2953**	**3442**	**3584**
Diameter	m	AC	8	14	8	14	8	16	8	8
Max Dynamic Pressure	Pa	AC	4259	1464	4259	1464	5922	2017	5791	2781
Inflatable Mass	kg	AC	85	204			113	395	111	60
Max Heat Rate	W/cm2	AC	108.7	44.5	108.6	44.5	111	48	67	49
Heat Load	MJ/m2	AC	109	44	109	44	80	26	41	51
TPS Mass	kg	AC	347	524			367	685	304	183
Rigid Diameter	m	AC	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Rigid Heatshield Mass	kg	AC	91	91			91	91	91	91
Payload Adaptor Mass	kg	AC	71	71			71	71	71	71
Separation Mass	kg	AC	58	66			59	76	58	53
Diameter	m	Entry	8	8	8	14				
Max Dynamic Pressure	Pa	Entry	1248	1147	1460	500				
Inflatable Mass	kg	Entry	40	38	85	204				
Max Heat Rate	W/cm2	Entry	5.0	4.5	5	2				
Heat Load	MJ/m2	Entry	14.8	15.1	17	8				
TPS Mass	kg	Entry	198	165	417	744				
Rigid Diameter	m	Entry	3.6	3.6						
Rigid Heatshield Mass	kg	Entry	64	64	91	91				
Payload Adaptor Mass	kg	Entry	64	61	71	71				
Separation Mass	kg	Entry	45	44	60	72				

TPS Diameter Sweep Trade

(Summary)

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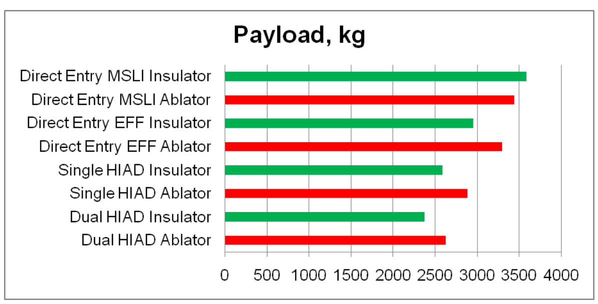

Proposed Model Improvements

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- FEA for structural & load bearing components (rigid section, payload adaptor, separation mechanism, …)
- Softgood loads are not constrained by allowable fabric seam-loads
- Aeroelastic effects are not included (assess flutter and localized heating)
- Leaks & Ullage(need more accurate assessment)
- Inflation system (need more detailed design)
- Determine minimum diameter limit
  - Allowable max heat rate
  - Angle of attack and required backshell cover/TPS mass penalty
  - Packaging
- Complete packaging associated and mass penalties

Proposed Model Improvements, cont.

EDL-SA

- CG/Bank maneuver mechanism
- Payload shroud, RCS attachment, and load path
- Payload rover
- Better understanding of separation concept (& associated mass penalty)
- Develop MER for sensor integration package (MEDLI?)
- Finish aeroshell CAD modeling (payload, engines, tanks, ….) for 6 dof
- …

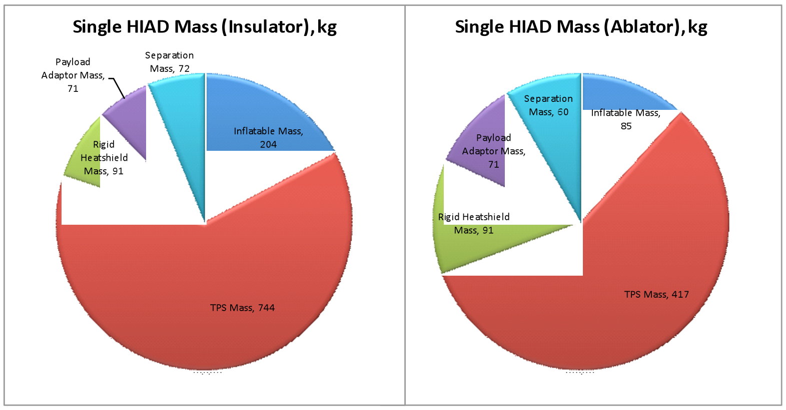
Summary

- The first mass model iteration has been completed with the following models:
  - Simulation model
  - HIAD model
  - Engine model
  - TPS models

BACKUP SLIDES

Mass Breakdown

EDL-SA



6.1.1 Component Mass Models: Descent Stage

D.R. Komar

Background

- Constructed parametric descent stage model calibrated to DRA5 for Year 1 sizing analysis
- Year 1 model scaled for EFF application resulted in extremely poor preliminary performance
- Constructed parametric descent stage model calibrated to MSL for EFF sizing analysis
- Performed propulsion trades to identify mass reduction opportunities for EFF
- Updated EFF parametric model to include propulsion system using pump-fed NTO/MMH engine

Descent Stage Parametric Model Sizing Trends as a function of Payload

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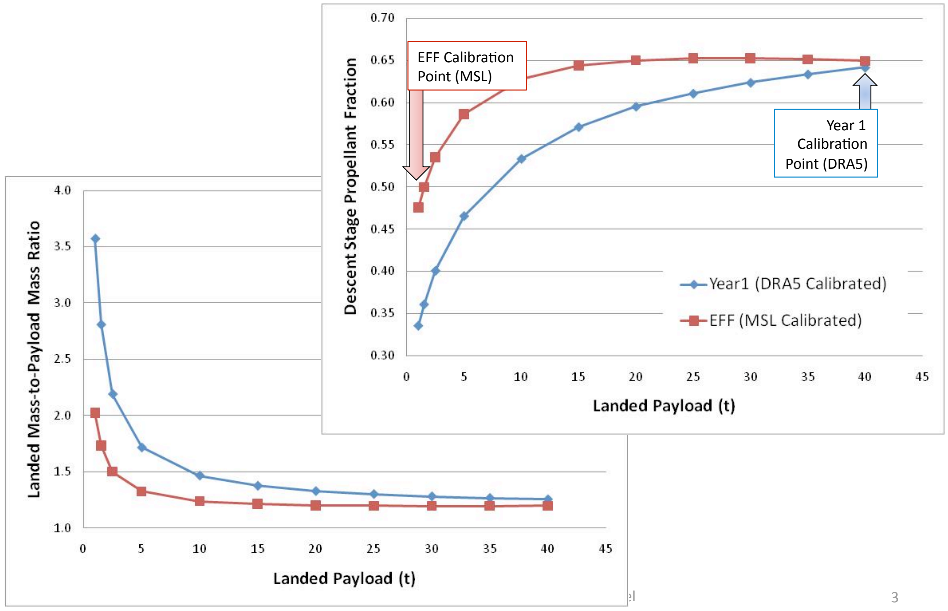

Propulsion Trades for EFF

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- Assessed descent stage propulsion system options to identify mass savings opportunities for EFF
  - Pressure-fed NTO/MMH
  - Pump-fed NTO/MMH
  - Pump-fed LOX/CH4
- Pump-fed NTO/MMH selected based on mass performance
  - Mission Risk
    - Impact not quantitatively evaluated
  - Development Risk
    - Throttling to 21% for landing requires 2 engines OFF and 2 engines throttled to 42%
    - Unknown whether pump-fed RS-72 is throttleable, but it is required for this application

	Press-Fed NTO/MMH	Pump-Fed NTO/MMH	Pump-Fed LOX/CH4
Dry Mass w/ Growth	**1,480**	**1,124**	**1,232**
Primary Body Structure	67	56	76
Secondary Body Structure	4	3	4
Thermal Protection System	8	7	9
Space Engines & Installation	245	134	142
RCS Engines & Installation	135	75	75
OMS Fuel Tanks & Feed/Fill/Drain System	111	58	82
OMS Oxidizer Tanks & Feed/Fill/Drain System	107	57	68
RCS Fuel Tanks & Feed/Fill/Drain System	0	34	34
RCS Oxidizer Tanks & Feed/Fill/Drain System	0	35	35
Pressurization System	22	9	11
Batteries	24	24	24
PMAD	65	65	65
Command, Control, and Data Handling	6	6	6
Guidance & Navigation	10	10	10
Communications	17	17	17
Cabling and Instrumentation	15	15	15
Heat Acquisition	11	11	11
Heat Transport	27	27	27
Heat Rejection	22	22	22
Landing Legs	95	86	90
MGA + PjMR	490	372	408
Inert Mass	**38**	**33**	**140**
OMS/RCS Press	5	4	5
Residual OMS Fuel	5	4	2
Residual RCS Fuel	8	7	7
Boiloff OMS Fuel	0	0	22
Residual OMS Oxidizer	8	6	7
Residual RCS Oxidizer	12	12	12
Boiloff OMS Oxidizer	0	0	84
Propellant	**1,623**	**1,452**	**1,442**
Usable OMS Fuel	234	196	110
Usable OMS Oxidizer	386	324	374
Usable RCS Fuel	378	352	361
Usable RCS Oxidizer	624	580	596
Gross Mass	**3,141**	**2,609**	**2,813**

Mars Aero-Capture (MAC) Element Sizing Assumptions

EDL-SA

- **General**
  - Parametrically sized power systems
  - All other subsystem mass (including HIAD structure, TPS, inflation systems, etc…) provided by Samareh
  - Mass growth allowance (MGA) and project managers reserve (PjMR) applied as a percentage of the current best estimate (CBE) mass for all subsystems to get predicted mass
- **Power**
  - 1 x 3-junction GaAs solar array mounted to body provide 0.5 kW power for coast
  - 115 volt AC power management and distribution system sized for 0.5 kW peak load (η = 90%)
  - Subsystem is jettisoned prior to descent orbit insertion

Descent Stage (DS) Element Sizing Assumptions

EDL-SA

- **Structure & Protection**
  - 2.6 m dia cylindrical stage, height determined from tank lengths
  - Aluminum-lithium structure
  - 5% secondary structure fraction
  - Landing gear 2.5% of landed mass
  - 5 cm of multi-layer insulation (@ 39.4 kg/m^3) covering exterior structure
- **Subsystems (Power, TCS, Avionics)**
  - 2 x 1 kW Li-Ion batteries provide 2 hours of power for entry and landing
  - 115 volt AC power management and distribution system sized for 1 kW peak load (η = 90%)
  - Power during trans-Mars coast provided by solar arrays on MAC element
  - Ammonia cooling loop collects heat from coldplates (up to 1 kW) for heat rejection via body mounted radiator
  - Avionics (including CCDH, communications, GN&C and instrumentation) consistent with MSL

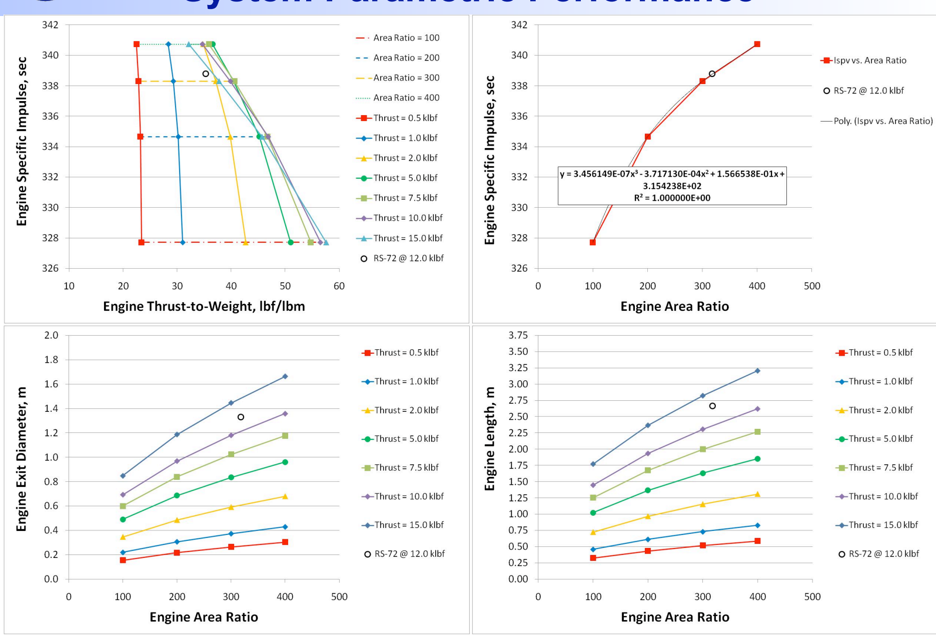
Descent Stage (DS) Element Sizing Assumptions (cont.)

EDL-SA

- **Main Propulsion – NTO/MMH**
  - 4 pump-fed engines sized to required stage thrust-to-weight at powered descent initiation
    - Engine mixture ratio = 2.05
    - Engine chamber pressure = 856 psia
    - Engine area ratio = 300
    - Engine C* efficiency = 91.9%
    - Engine Isp efficiency = 93.3%
    - Gimbals provided for thrust vector control
    - ~ 21% throttle required for landing
  - Performance predictions based on parametric model (see next slide) calibrated to Rocketdyne's RS-72
  - 1 NTO tank + 1 MMH tank
    - Graphite-wrapped aluminum spheres
    - 40 psia storage pressure
    - Heaters for long term storage
    - 10 layers multi-layer insulation
    - Gaseous helium pressurization system w/ 6000 psia graphite-wrapped aluminum spherical tanks
- **RCS Propulsion – NTO/MMH**
  - 16 pressure-fed RCS thrusters each @ 100 lbf thrust
    - Thruster mixture ratio = 1.65
    - Thruster chamber pressure = 125 psia
    - Thruster expansion ratio = 40
    - Thruster C* efficiency = 98%
    - Thruster Isp efficiency = 92%
  - Parametric performance model predicts RCS vacuum Isp = 301.3 sec
  - 1 NTO tank + 1 MMH tank
    - Graphite-wrapped aluminum spheres
    - 225 psia storage pressure
    - Heaters for long term storage
    - 10 layers multi-layer insulation
    - Gaseous helium pressurization system w/ 6000 psia graphite-wrapped aluminum spherical tanks

Pump-fed NTO/MMH Propulsion System Parametric Performance

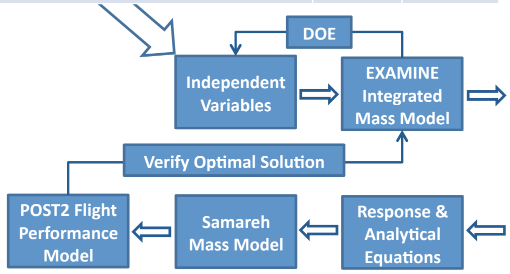
EDL-SA



Design of Experiments (DOE) Process & Independent Variables

EDL-SA

Response Surface & Analytical Equation Independent Variables	Lower Bound	Upper Bound
x1: Payload to Mars Surface	1 t	5 t
x2: Terminal Descent Insertion ΔV	200 m/s	1000 m/s
x3: Descent Stage Initial T/W (Mars g's)	0.5 g's	5.0 g's
x4: Descent Stage Engine Area Ratio	100	400
x5: A/C HIAD Mass (w/o RCS+power+margin)	0.4 t	1.6 t
x6: A/C Apo-/Peri-Correction ΔV	0 m/s	200 m/s
x7: Descent Initiation ΔV	0 m/s	300 m/s
x8: Entry HIAD Mass (w/o RCS+power+margin)	0.1 t	1 t
x9: Percent Total Margin (CBE-based)	25%	100%



Response Surface & Analytical Equation Dependent Variables
y1: Descent stage (DS) initial mass (kg)
y2: Mars aerocapture (MAC) initial mass (kg)
y3: Stack mass @ launch (kg)
y4: Stack mass @ arrival (kg)
y5: Stack mass @ entry (kg)
y6: Stack mass @ TDI (kg)
y7: Stack mass @ landing (kg)
y8: DS main propellant mass (terminal landing) (kg)
y9: DS RCS propellant mass (terminal landing) (kg)
y10: DS RCS propellant mass (MCC, A/C, entry) (kg)
y11: DS initial T/W (Earth g's)
y12: DS engine vacuum Isp (sec)
y13: DS engine exit diameter (m)
y14: DS engine length (m)
y15: DS thrust per engine (lbf)
y16: Jettison mass @ post-capture (kg)
y17: Jettison mass @ pre-DOI (kg)
y18: Jettison mass @ post-entry (kg)

Mission Performance Summary for Dual HIAD Ablator Case

EDL-SA

Maneuver/Burn	Delta-V (m/s)	Specific Impulse (sec)	Comments
Mid-Course Correction (RCS)	55	301.3	
Apo-/Peri-Correction (RCS)	150	301.3	
Descent Orbit Insertion (RCS for De-Orbit)	102.5	301.3	
Entry Maneuvers (RCS)	---	301.3	200 kg prop allocated for bank control
Terminal Descent Insertion (RCS for Landing)	30	301.3	
Terminal Descent Insertion (Main for Landing)	494.8	338.3	

	Stack Mass, kg	Final Mass, kg	Main Prop Mass, kg	RCS Prop Mass, kg	MAC Jettison Mass, kg	MAC Stage Mass, kg		DS Stage Mass, kg	Payload Mass, kg
Launch	**7217.18**					**1809.15**		**2781.42**	**2626.61**
MidCourse Correction	7217.18	7084.09		133.09		1809.15	1	2648.33	
Arrival	**7084.09**					**1809.15**		**2648.33**	**2626.61**
Aerocapture	**7084.09**					**1809.15**		**2648.33**	**2626.61**
Post Aerocapture HIAD1 Jettison	7084.09	6109.83			974.26	834.89		2648.33	
Apo-/Peri-Correction	6109.83	5807.42		302.41		834.89	1	2345.92	
Pre-DOI PVArray Jettison	5807.42	5586.28			221.15	613.75		2345.92	
Descent Orbit Insertion	5586.28	5395.79		190.49		613.75	1	2155.44	
Entry	**5395.79**					**613.75**		**2155.44**	**2626.61**
Entry RCS Maneuvers	5395.79	5195.79		200.00		613.75	1	1955.44	
MAC Jettison	5195.79	4582.05			613.75	0.00		1955.44	
TDI	**4582.05**					**0.00**		**1955.44**	**2626.61**
Terminal Descent Maneuver	4582.05	3900.92	634.84	46.28		0.00	1	1274.31	
Landing	**3900.92**					**0.00**		**1274.31**	**2626.61**

Descent Stage Mass Comparison

EDL-SA

All Masses in kg	Dual HIAD		Single HIAD		Direct Entry			
	Ablator	Insulator	Ablator	Insulator	Ablator (EFF V_{entry})	Insulator (EFF V_{entry})	Ablator (MSL V_{entry})	Insulator (MSL V_{entry})
Dry Mass w/ Growth	**1,240**	**1,201**	**1,287**	**1,205**	**1,324**	**1,260**	**1,330**	**1,359**
Primary Body Structure	63	60	66	55	71	58	70	72
Secondary Body Structure	3	3	3	3	4	3	4	4
Thermal Protection System	8	7	8	7	9	7	8	9
Space Engines & Installation	164	152	177	155	196	181	199	208
RCS Engines & Installation	75	75	75	75	75	75	75	75
OMS Fuel Tanks & Feed/Fill/Drain System	59	57	60	56	63	59	63	64
OMS Oxidizer Tanks & Feed/Fill/Drain System	61	60	63	58	66	61	65	67
RCS Fuel Tanks & Feed/Fill/Drain System	33	33	34	34	27	27	27	27
RCS Oxidizer Tanks & Feed/Fill/Drain System	34	34	35	35	28	28	28	28
Pressurization System	9	8	10	8	7	5	7	7
Batteries	24	24	24	24	24	24	24	24
PMAD	28	28	28	28	28	28	28	28
Command, Control, and Data Handling	48	48	48	48	48	48	48	48
Guidance & Navigation	36	36	36	36	36	36	36	36
Communications	26	26	26	26	26	26	26	26
Cabling and Instrumentation	24	24	24	24	24	24	24	24
Heat Acquisition	9	9	9	9	9	9	9	9
Heat Transport	11	11	11	11	11	11	11	11
Heat Rejection	17	17	17	17	17	17	17	17
Landing Legs	98	90	105	96	116	114	120	124
MGA + PjMR	411	398	426	399	438	417	440	450
Reserve/Residual/Press Mass	**34**	**32**	**38**	**32**	**28**	**20**	**27**	**29**
OMS/RCS Press	4	4	4	4	2	2	2	2
Residual OMS Fuel	4	4	5	3	6	3	5	6
Residual RCS Fuel	7	6	7	7	3	3	3	3
Boiloff OMS Fuel	0	0	0	0	0	0	0	0
Residual OMS Oxidizer	9	8	10	6	12	7	11	12
Residual RCS Oxidizer	11	10	12	12	5	5	5	5
Boiloff OMS Oxidizer	0	0	0	0	0	0	0	0
Inert Mass	**1,274**	**1,233**	**1,325**	**1,236**	**1,351**	**1,280**	**1,357**	**1,387**
Propellant	**1,507**	**1,399**	**1,687**	**1,387**	**1,281**	**915**	**1,229**	**1,319**
Usable OMS Fuel	208	188	241	147	292	174	275	304
Usable OMS Oxidizer	427	385	494	301	599	357	564	623
Usable RCS Fuel	329	312	359	354	147	145	147	148
Usable RCS Oxidizer	543	515	593	584	242	240	243	245
Gross Mass	**2,781**	**2,632**	**3,012**	**2,624**	**2,632**	**2,196**	**2,586**	**2,706**

Conclusions

EDL-SA

- RSE methods employed in EDL-SA efforts increased analytical efficiency and utility by...
  - Eliminating manual trajectory-sizing iterations
  - Enabling mass closure within the trajectory optimization framework
  - Enabling optimization of system configuration and elements sizing variables in conjunction with trajectory optimization
- For each of the 8 EFF cases, final solutions were verified in EXAMINE and show reasonably small errors due to the RSE methods used.

BACKUP SLIDES

EXAMINE (AIAA-2008-7845, Komar et al.)
(Exploration Architecture Model for IN-space and Earth-to-orbit)

EXAMINE is a general purpose framework for exploration architecture modeling with destinations to any celestial body in the solar system.

- **Architecture Trade Manager (ATM)**
  - Manages data within the framework, and controls global convergence of the integrated architecture.
- **EXAMINE Segment Model (ESM)**
  - Parametric subsystem sizing models employed to buildup desired functional element models for each ConOps
  - Appropriate for launch vehicle stages, in-space transfer stages, lander stages, entry vehicles, transfer habitats, orbital platforms, surface habitats
  - Current effort sizes descent stage (DS) employing supersonic retro-propulsion (SRP) technology AND sizes portion of Mars Aero-Capture (MAC) element RCS system

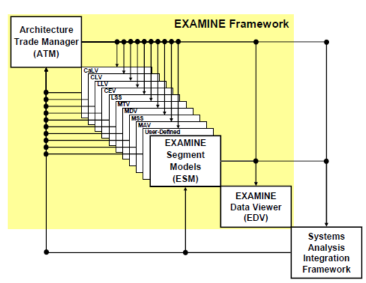
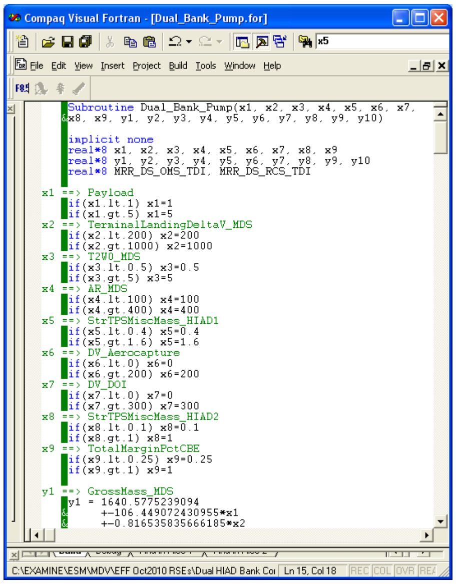


Figure 1. EXAMINE Framework

EXAMINE capability demonstrated and verified through various Cx Lunar architecture trade studies, independent Mars architecture analysis, and recently to assess launch, mission and transportation options in support of the Review of U.S. Human Space Flight Plans Committee and subsequent NASA level I & II study efforts (HLLV, HEFT).

Response and Analytical Equations Process Overview, cont.

EDL-SA



Analytical Equations

y[11] = x[3] * 0.379

y[15] = y[11] * (y[6] * 9.806) / 4. / 4.4482

y[12] = 3.45614E-07*x[4]*x[4]*x[4] - 3.71713E-04*x[4]*x[4] + 1.566538E-01*x[4] + 315.4238

y[13] = 0.00073747 * sqrt(y[15]) * pow(x[4], 0.4861566)

y[14] = 0.00197338 * sqrt(y[15]) * pow(x[4], 0.431242)

MRR_DS_Landing = exp(30. / (9.806 * 230.))

y[9] = y[6] * (1. - 1. / MRR_DS_RCS)

MRR_DS_Landing= exp(x[2] / (9.806 * y[12]))

y[8] = y[6] * (1. - 1. / MRR_DS_OMS)

y[16] = (1. + x[9]) * 1000. * x[5]

y[17] = (1. + x[9]) * 147.92

y[18] = y[2] - y[16] - y[17]

Event Mass Tracking

EDL-SA

Dual HIAD Ablator

	Stack Mass, kg	Final Mass, kg	Main Prop Mass, kg	RCS Prop Mass, kg	MAC Jettison Mass, kg	MAC Stage Mass, kg		DS Stage Mass, kg	Payload Mass, kg
Launch	**7217.18**					**1809.15**		**2781.42**	**2626.61**
MidCourse Correction	7217.18	7084.09		133.09		1809.15	1	2648.33	
Arrival	**7084.09**					**1809.15**		**2648.33**	**2626.61**
Aerocapture	**7084.09**					**1809.15**		**2648.33**	**2626.61**
Post Aerocapture HIAD1 Jettison	7084.09	6109.83			974.26	834.89		2648.33	
Apo-/Peri-Correction	6109.83	5807.42		302.41		834.89	1	2345.92	
Pre-DOI PVArray Jettison	5807.42	5586.28			221.15	613.75		2345.92	
Descent Orbit Insertion	5586.28	5395.79		190.49		613.75	1	2155.44	
Entry	**5395.79**					**613.75**		**2155.44**	**2626.61**
Entry RCS Maneuvers	5395.79	5195.79		200.00		613.75	1	1955.44	
MAC Jettison	5195.79	4582.05			613.75	0.00		1955.44	
TDI	**4582.05**					**0.00**		**1955.44**	**2626.61**
Terminal Descent Maneuver	4582.05	3900.92	634.84	46.28		0.00	1	1274.31	
Landing	**3900.92**					**0.00**		**1274.31**	**2626.61**

Dual HIAD Insulator

	Stack Mass, kg	Final Mass, kg	Main Prop Mass, kg	RCS Prop Mass, kg	MAC Jettison Mass, kg	MAC Stage Mass, kg		DS Stage Mass, kg	Payload Mass, kg
Launch	**7208.99**					**2205.66**		**2632.21**	**2371.12**
MidCourse Correction	7208.99	7076.05		132.94		2205.66	1	2499.27	
Arrival	**7076.05**					**2205.66**		**2499.27**	**2371.12**
Aerocapture	**7076.05**					**2205.66**		**2499.27**	**2371.12**
Post Aerocapture HIAD1 Jettison	7076.05	5646.56			1429.49	776.17		2499.27	
Apo-/Peri-Correction	5646.56	5367.08		279.48		776.17	1	2219.79	
Pre-DOI PVArray Jettison	5367.08	5145.93			221.15	555.02		2219.79	
Descent Orbit Insertion	5145.93	4974.16		171.78		555.02	1	2048.02	
Entry	**4974.16**					**555.02**		**2048.02**	**2371.12**
Entry RCS Maneuvers	4974.16	4774.16		200.00		555.02	1	1848.02	
MAC Jettison	4774.16	4219.14			555.02	0.00		1848.02	
TDI	**4219.14**					**0.00**		**1848.02**	**2371.12**
Terminal Descent Maneuver	4219.14	3603.95	572.57	42.62		0.00	1	1232.83	
Landing	**3603.95**					**0.00**		**1232.83**	**2371.12**

Event Mass Tracking

EDL-SA

Single HIAD Ablator

	Stack Mass, kg	Final Mass, kg	Main Prop Mass, kg	RCS Prop Mass, kg	MAC Jettison Mass, kg	MAC Stage Mass, kg		DS Stage Mass, kg	Payload Mass, kg
Launch	**7197.63**					**1304.45**		**3011.85**	**2881.33**
MidCourse Correction	7197.63	7064.90		132.73		1304.45	1	2879.12	
Arrival	**7064.90**					**1304.45**		**2879.12**	**2881.33**
Aerocapture	**7064.90**					**1304.45**		**2879.12**	**2881.33**
Post Aerocapture HIAD1 Jettison	7064.90	7064.90			0.00	1304.45		2879.12	
Apo-/Peri-Correction	7064.90	6715.22		349.68		1304.45	1	2529.44	
Pre-DOI PVArray Jettison	6715.22	6494.08			221.15	1083.31		2529.44	
Descent Orbit Insertion	6494.08	6275.10		218.98		1083.31	1	2310.46	
Entry	**6275.10**					**1083.31**		**2310.46**	**2881.33**
Entry RCS Maneuvers	6275.10	6075.10		200.00		1083.31	1	2110.46	
MAC Jettison	6075.10	4991.79			1083.31	0.00		2110.46	
TDI	**4991.79**					**0.00**		**2110.46**	**2881.33**
Terminal Descent Maneuver	4991.79	4206.53	734.84	50.42		0.00	1	1325.20	
Landing	**4206.53**					**0.00**		**1325.20**	**2881.33**

Single HIAD Insulator

	Stack Mass, kg	Final Mass, kg	Main Prop Mass, kg	RCS Prop Mass, kg	MAC Jettison Mass, kg	MAC Stage Mass, kg		DS Stage Mass, kg	Payload Mass, kg
Launch	**7200.88**					**1988.47**		**2623.61**	**2588.80**
MidCourse Correction	7200.88	7068.09		132.79		1988.47	1	2490.82	
Arrival	**7068.09**					**1988.47**		**2490.82**	**2588.80**
Aerocapture	**7068.09**					**1988.47**		**2490.82**	**2588.80**
Post Aerocapture HIAD1 Jettison	7068.09	7068.09			0.00	1988.47		2490.82	
Apo-/Peri-Correction	7068.09	6718.25		349.84		1988.47	1	2140.98	
Pre-DOI PVArray Jettison	6718.25	6497.11			221.15	1767.32		2140.98	
Descent Orbit Insertion	6497.11	6284.75		212.36		1767.32	1	1928.62	
Entry	**6284.75**					**1767.32**		**1928.62**	**2588.80**
Entry RCS Maneuvers	6284.75	6084.75		200.00		1767.32	1	1728.62	
MAC Jettison	6084.75	4317.42			1767.32	0.00		1728.62	
TDI	**4317.42**					**0.00**		**1728.62**	**2588.80**
Terminal Descent Maneuver	4317.42	3825.30	448.51	43.61		0.00	1	1236.50	
Landing	**3825.30**					**0.00**		**1236.50**	**2588.80**

Event Mass Tracking

EDL-SA

Direct Entry Ablator (EFF V_{entry})

	Stack Mass, kg	Final Mass, kg	Main Prop Mass, kg	RCS Prop Mass, kg	MAC Jettison Mass, kg	MAC Stage Mass, kg		DS Stage Mass, kg	Payload Mass, kg
Launch	**7197.45**					**1270.96**		**2632.46**	**3294.03**
MidCourse Correction	7197.45	7064.72		132.73		1270.96	1	2499.73	
Arrival	**7064.72**					**1270.96**		**2499.73**	**3294.03**
Aerocapture	**7064.72**					**1270.96**		**2499.73**	**3294.03**
Post Aerocapture HIAD1 Jettison	7064.72	7064.72			0.00	1270.96		2499.73	
Apo-/Peri-Correction	7064.72	7064.72		0.00		1270.96	1	2499.73	
Pre-DOI PVArray Jettison	7064.72	6843.58			221.15	1049.81		2499.73	
Descent Orbit Insertion	6843.58	6843.58		0.00		1049.81	1	2499.73	
Entry	**6843.58**					**1049.81**		**2499.73**	**3294.03**
Entry RCS Maneuvers	6843.58	6643.58		200.00		1049.81	1	2299.73	
MAC Jettison	6643.58	5593.76			1049.81	0.00		2299.73	
TDI	**5593.76**					**0.00**		**2299.73**	**3294.03**
Terminal Descent Maneuver	5593.76	4645.38	891.88	56.50		0.00	1	1351.35	
Landing	**4645.38**					**0.00**		**1351.35**	**3294.03**

Direct Entry Insulator (EFF V_{entry})

	Stack Mass, kg	Final Mass, kg	Main Prop Mass, kg	RCS Prop Mass, kg	MAC Jettison Mass, kg	MAC Stage Mass, kg		DS Stage Mass, kg	Payload Mass, kg
Launch	**7200.46**					**1727.38**		**2195.58**	**3277.50**
MidCourse Correction	7200.46	7067.68		132.78		1727.38	1	2062.79	
Arrival	**7067.68**					**1727.38**		**2062.79**	**3277.50**
Aerocapture	**7067.68**					**1727.38**		**2062.79**	**3277.50**
Post Aerocapture HIAD1 Jettison	7067.68	7067.68			0.00	1727.38		2062.79	
Apo-/Peri-Correction	7067.68	7067.68		0.00		1727.38	1	2062.79	
Pre-DOI PVArray Jettison	7067.68	6846.53			221.15	1506.24		2062.79	
Descent Orbit Insertion	6846.53	6846.53		0.00		1506.24	1	2062.79	
Entry	**6846.53**					**1506.24**		**2062.79**	**3277.50**
Entry RCS Maneuvers	6846.53	6646.53		200.00		1506.24	1	1862.79	
MAC Jettison	6646.53	5140.29			1506.24	0.00		1862.79	
TDI	**5140.29**					**0.00**		**1862.79**	**3277.50**
Terminal Descent Maneuver	5140.29	4557.86	530.51	51.92		0.00	1	1280.36	
Landing	**4557.86**					**0.00**		**1280.36**	**3277.50**

Event Mass Tracking

EDL-SA

Direct Entry Ablator (MSL V_{entry})

	Stack Mass, kg	Final Mass, kg	Main Prop Mass, kg	RCS Prop Mass, kg	MAC Jettison Mass, kg	MAC Stage Mass, kg		DS Stage Mass, kg	Payload Mass, kg
Launch	**7197.45**					**1169.49**		**2585.62**	**3442.33**
MidCourse Correction	7197.45	7064.72		132.73		1169.49	1	2452.90	
Arrival	**7064.72**					**1169.49**		**2452.90**	**3442.33**
Aerocapture	**7064.72**					**1169.49**		**2452.90**	**3442.33**
Post Aerocapture HIAD1 Jettison	7064.72	7064.72			0.00	1169.49		2452.90	
Apo-/Peri-Correction	7064.72	7064.72		0.00		1169.49	1	2452.90	
Pre-DOI PVArray Jettison	7064.72	6843.58			221.15	948.35		2452.90	
Descent Orbit Insertion	6843.58	6843.58		0.00		948.35	1	2452.90	
Entry	**6843.58**					**948.35**		**2452.90**	**3442.33**
Entry RCS Maneuvers	6843.58	6643.58		200.00		948.35	1	2252.90	
MAC Jettison	6643.58	5695.23			948.35	0.00		2252.90	
TDI	**5695.23**					**0.00**		**2252.90**	**3442.33**
Terminal Descent Maneuver	5695.23	4799.19	838.51	57.53		0.00	1	1356.86	
Landing	**4799.19**					**0.00**		**1356.86**	**3442.33**

Direct Entry Insulator (MSL V_{entry})

	Stack Mass, kg	Final Mass, kg	Main Prop Mass, kg	RCS Prop Mass, kg	MAC Jettison Mass, kg	MAC Stage Mass, kg		DS Stage Mass, kg	Payload Mass, kg
Launch	**7196.38**					**905.62**		**2706.35**	**3584.41**
MidCourse Correction	7196.38	7063.67		132.71		905.62	1	2573.64	
Arrival	**7063.67**					**905.62**		**2573.64**	**3584.41**
Aerocapture	**7063.67**					**905.62**		**2573.64**	**3584.41**
Post Aerocapture HIAD1 Jettison	7063.67	7063.67			0.00	905.62		2573.64	
Apo-/Peri-Correction	7063.67	7063.67		0.00		905.62	1	2573.64	
Pre-DOI PVArray Jettison	7063.67	6842.52			221.15	684.47		2573.64	
Descent Orbit Insertion	6842.52	6842.52		0.00		684.47	1	2573.64	
Entry	**6842.52**					**684.47**		**2573.64**	**3584.41**
Entry RCS Maneuvers	6842.52	6642.52		200.00		684.47	1	2373.64	
MAC Jettison	6642.52	5958.05			684.47	0.00		2373.64	
TDI	**5958.05**					**0.00**		**2373.64**	**3584.41**
Terminal Descent Maneuver	5958.05	4971.54	926.34	60.18		0.00	1	1387.13	
Landing	**4971.54**					**0.00**		**1387.13**	**3584.41**

RSE and Case Error Verification

EDL-SA

Dual HIAD Ablator

x1	Payload	2.63		
x2	TerminalLandingDeltaV_MDS	494.78		
x3	T2W0_MDS	3.70		
x4	AR_MDS	300.00		
x5	StrTPSMiscMass_HIAD1	0.651678		
x6	DV_Aerocapture	150.00		
x7	DV_DOI	102.52		
x8	StrTPSMiscMass_HIAD2	0.410507		
x9	TotalMarginPctCBE	0.495		
	BANK CONTROL (200 kg) CASE			
		RSE	**EXAMINE**	**ERROR**
y1	GrossMass_MDS	2735.22	2781.42	-1.7%
y2	GrossMass_MAB	1725.59	1809.15	-4.6%
y3	StackMass_Launch	7200.00	7217.18	-0.2%
y4	StackMass_Arrival	7067.00	7084.09	-0.2%
y5	StackMass_Entry	5375.13	5395.79	-0.4%
y6	StackMass_TDI	4551.71	4582.05	-0.7%
y7	StackMass_Landed	3883.03	3900.92	-0.5%
y8	OMSPropMass_Landing	630.68	634.84	-0.7%
y9	RCSPropMass_Landing	45.98	46.28	-0.6%
y10	RCSPropMass_ACEntry	813.56	825.98	-1.5%
y11	T2Winit_MDS_EarthG	1.4023	1.4023	0.0%
y12	EngineVacuumIsp_DS	338.30	338.30	0.0%
y13	EngineExitDiameter_DS	0.7002	0.7023	-0.3%
y14	EngineLength_DS	1.3698	1.3718	-0.1%
y15	ThrustPerEngine_DS	3519.16	3541.40	-0.6%
y16	JettMass_PostCapture	974.26	974.26	0.0%
y17	JettMass_PreDOI	221.14	221.15	0.0%
y18	JettMass_PostEntry	530.19	613.75	-13.6%

Dual HIAD Insulator

x1	Payload	2.37		
x2	TerminalLandingDeltaV_MDS	483.85		
x3	T2W0_MDS	3.70		
x4	AR_MDS	300.00		
x5	StrTPSMiscMass_HIAD1	0.956182		
x6	DV_Aerocapture	150.00		
x7	DV_DOI	100.32		
x8	StrTPSMiscMass_HIAD2	0.371226		
x9	TotalMarginPctCBE	0.495		
	BANK CONTROL (200 kg) CASE			
		RSE	**EXAMINE**	**ERROR**
y1	GrossMass_MDS	2603.48	2632.21	-1.1%
y2	GrossMass_MAB	2155.65	2205.66	-2.3%
y3	StackMass_Launch	7199.99	7208.99	-0.1%
y4	StackMass_Arrival	7067.12	7076.05	-0.1%
y5	StackMass_Entry	4958.75	4974.16	-0.3%
y6	StackMass_TDI	4199.42	4219.14	-0.5%
y7	StackMass_Landed	3591.93	3603.95	-0.3%
y8	OMSPropMass_Landing	569.93	572.57	-0.5%
y9	RCSPropMass_Landing	42.42	42.62	-0.5%
y10	RCSPropMass_ACEntry	777.04	784.19	-0.9%
y11	T2Winit_MDS_EarthG	1.4023	1.4023	0.0%
y12	EngineVacuumIsp_DS	338.30	338.30	0.0%
y13	EngineExitDiameter_DS	0.6726	0.6739	-0.2%
y14	EngineLength_DS	1.3158	1.3164	0.0%
y15	ThrustPerEngine_DS	3246.78	3260.91	-0.4%
y16	JettMass_PostCapture	1429.49	1429.49	0.0%
y17	JettMass_PreDOI	221.14	221.15	0.0%
y18	JettMass_PostEntry	505.01	555.02	-9.0%

RSE and Case Error Verification

EDL-SA

Single HIAD Ablator

		RSE	EXAMINE	ERROR
x1	Payload	2.88		
x2	TerminalLandingDeltaV_MDS	528.29		
x3	T2W0_MDS	3.70		
x4	AR_MDS	300.00		
x6	DV_Aerocapture	150.00		
x7	DV_DOI	101.36		
x8	StrTPSMiscMass_HIAD2	0.72		
x9	TotalMarginPctCBE	0.495		
	BANK CONTROL (200 kg) CASE			
y1	GrossMass_MDS	3014.21	3011.85	0.1%
y2	GrossMass_MAB	1231.57	1304.45	-5.6%
y3	StackMass_Launch	7200.00	7197.63	0.0%
y4	StackMass_Arrival	7067.23	7064.90	0.0%
y5	StackMass_Entry	6277.31	6275.10	0.0%
y6	StackMass_TDI	4994.01	4991.79	0.0%
y7	StackMass_Landed	4207.97	4206.53	0.0%
y8	OMSPropMass_Landing	735.59	734.84	0.1%
y9	RCSPropMass_Landing	50.44	50.42	0.0%
y10	RCSPropMass_ACEntry	901.54	901.38	0.0%
y11	T2Winit_MDS_EarthG	1.4023	1.4023	0.0%
y12	EngineVacuumIsp_DS	338.30	338.30	0.0%
y13	EngineExitDiameter_DS	0.7334	0.7330	0.1%
y14	EngineLength_DS	1.4348	1.4319	0.2%
y15	ThrustPerEngine_DS	3861.11	3858.08	0.1%
y16	JettMass_PostCapture	0.00	0.00	#DIV/0!
y17	JettMass_PreDOI	221.14	221.15	0.0%
y18	JettMass_PostEntry	1010.43	1083.31	-6.7%

Single HIAD Insulator

		RSE	EXAMINE	ERROR
x1	Payload	2.59		
x2	TerminalLandingDeltaV_MDS	363.89		
x3	T2W0_MDS	3.70		
x4	AR_MDS	300.00		
x6	DV_Aerocapture	150.00		
x7	DV_DOI	98.20		
x8	StrTPSMiscMass_HIAD2	1.18		
x9	TotalMarginPctCBE	0.495		
	BANK CONTROL (200 kg) CASE			
y1	GrossMass_MDS	2622.74	2623.61	0.0%
y2	GrossMass_MAB	1973.51	1988.47	-0.8%
y3	StackMass_Launch	7200.01	7200.88	0.0%
y4	StackMass_Arrival	7067.24	7068.09	0.0%
y5	StackMass_Entry	6284.19	6284.75	0.0%
y6	StackMass_TDI	4316.86	4317.42	0.0%
y7	StackMass_Landed	3823.93	3825.30	0.0%
y8	OMSPropMass_Landing	449.33	448.51	0.2%
y9	RCSPropMass_Landing	43.60	43.61	0.0%
y10	RCSPropMass_ACEntry	894.68	894.99	0.0%
y11	T2Winit_MDS_EarthG	1.4023	1.4023	0.0%
y12	EngineVacuumIsp_DS	338.30	338.30	0.0%
y13	EngineExitDiameter_DS	0.6819	0.6817	0.0%
y14	EngineLength_DS	1.3340	1.3316	0.2%
y15	ThrustPerEngine_DS	3337.58	3336.87	0.0%
y16	JettMass_PostCapture	0.00	0.00	#DIV/0!
y17	JettMass_PreDOI	221.14	221.15	0.0%
y18	JettMass_PostEntry	1752.37	1767.32	-0.8%

RSE and Case Error Verification

EDL-SA

Direct Entry Ablator (EFF V_{entry})

		RSE	EXAMINE	ERROR
x1	Payload	3.29		
x2	TerminalLandingDeltaV_MDS	576.22		
x3	T2W0_MDS	3.70		
x4	AR_MDS	300.00		
x8	StrTPSMiscMass_HIAD2	0.70		
x9	TotalMarginPctCBE	0.495		
	BANK CONTROL (200 kg) CASE			
y1	GrossMass_MDS	2635.01	2632.46	0.1%
y2	GrossMass_MAB	1219.24	1270.96	-4.1%
y3	StackMass_Launch	7200.00	7197.45	0.0%
y4	StackMass_Arrival	7067.23	7064.72	0.0%
y5	StackMass_Entry	6846.08	6843.58	0.0%
y6	StackMass_TDI	5596.27	5593.76	0.0%
y7	StackMass_Landed	4647.43	4645.38	0.0%
y8	OMSPropMass_Landing	892.33	891.88	0.1%
y9	RCSPropMass_Landing	56.54	56.50	0.1%
y10	RCSPropMass_ACEntry	332.77	332.73	0.0%
y11	T2Winit_MDS_EarthG	1.4023	1.4023	0.0%
y12	EngineVacuumIsp_DS	338.30	338.30	0.0%
y13	EngineExitDiameter_DS	0.7764	0.7760	0.1%
y14	EngineLength_DS	1.5189	1.5157	0.2%
y15	ThrustPerEngine_DS	4326.75	4323.34	0.1%
y16	JettMass_PostCapture	0.00	0.00	#DIV/0!
y17	JettMass_PreDOI	221.14	221.15	0.0%
y18	JettMass_PostEntry	998.10	1049.81	-4.9%

Direct Entry Insulator (EFF V_{entry})

		RSE	EXAMINE	ERROR
x1	Payload	3.28		
x2	TerminalLandingDeltaV_MDS	361.38		
x3	T2W0_MDS	3.70		
x4	AR_MDS	300.00		
x8	StrTPSMiscMass_HIAD2	1.01		
x9	TotalMarginPctCBE	0.495		
	BANK CONTROL (200 kg) CASE			
y1	GrossMass_MDS	2195.12	2195.56	0.0%
y2	GrossMass_MAB	1715.36	1727.38	-0.7%
y3	StackMass_Launch	7200.00	7200.46	0.0%
y4	StackMass_Arrival	7067.23	7067.68	0.0%
y5	StackMass_Entry	6846.08	6846.53	0.0%
y6	StackMass_TDI	5139.84	5140.29	0.0%
y7	StackMass_Landed	4558.63	4557.86	0.0%
y8	OMSPropMass_Landing	530.50	530.51	0.0%
y9	RCSPropMass_Landing	51.93	51.92	0.0%
y10	RCSPropMass_ACEntry	332.77	332.78	0.0%
y11	T2Winit_MDS_EarthG	1.4023	1.4023	0.0%
y12	EngineVacuumIsp_DS	338.30	338.30	0.0%
y13	EngineExitDiameter_DS	0.7441	0.7438	0.0%
y14	EngineLength_DS	1.4556	1.4530	0.2%
y15	ThrustPerEngine_DS	3973.87	3972.86	0.0%
y16	JettMass_PostCapture	0.00	0.00	#DIV/0!
y17	JettMass_PreDOI	221.14	221.15	0.0%
y18	JettMass_PostEntry	1494.22	1506.24	-0.8%

RSE and Case Error Verification

EDL-SA

Direct Entry Ablator (MSL V_{entry})

x1	Payload	3.44		
x2	TerminalLandingDeltaV_MDS	528.37		
x3	T2W0_MDS	3.70		
x4	AR_MDS	300.00		
x8	StrTPSMiscMass_HIAD2	0.63		
x9	TotalMarginPctCBE	0.495		
	BANK CONTROL (200 kg) CASE			
		RSE	**EXAMINE**	**ERROR**
y1	GrossMass_MDS	2588.18	2585.61	0.1%
y2	GrossMass_MAB	1108.96	1169.49	-5.2%
y3	StackMass_Launch	7200.00	7197.45	0.0%
y4	StackMass_Arrival	7067.23	7064.72	0.0%
y5	StackMass_Entry	6846.08	6843.58	0.0%
y6	StackMass_TDI	5697.73	5695.23	0.0%
y7	StackMass_Landed	4801.35	4799.19	0.0%
y8	OMSPropMass_Landing	838.93	838.51	0.1%
y9	RCSPropMass_Landing	57.56	57.53	0.1%
y10	RCSPropMass_ACEntry	332.77	332.73	0.0%
y11	T2Winit_MDS_EarthG	1.4023	1.4023	0.0%
y12	EngineVacuumIsp_DS	338.30	338.30	0.0%
y13	EngineExitDiameter_DS	0.7834	0.7830	0.1%
y14	EngineLength_DS	1.5326	1.5294	0.2%
y15	ThrustPerEngine_DS	4405.20	4401.76	0.1%
y16	JettMass_PostCapture	0.00	0.00	#DIV/0!
y17	JettMass_PreDOI	221.14	221.15	0.0%
y18	JettMass_PostEntry	887.82	948.35	-6.4%

Direct Entry Insulator (MSL V_{entry})

x1	Payload	3.58		
x2	TerminalLandingDeltaV_MDS	560.61		
x3	T2W0_MDS	3.70		
x4	AR_MDS	300.00		
x8	StrTPSMiscMass_HIAD2	0.46		
x9	TotalMarginPctCBE	0.495		
	BANK CONTROL (200 kg) CASE			
		RSE	**EXAMINE**	**ERROR**
y1	GrossMass_MDS	2709.98	2706.35	0.1%
y2	GrossMass_MAB	822.13	905.62	-9.2%
y3	StackMass_Launch	7200.01	7196.38	0.1%
y4	StackMass_Arrival	7067.23	7063.67	0.1%
y5	StackMass_Entry	6846.09	6842.52	0.1%
y6	StackMass_TDI	5961.62	5958.05	0.1%
y7	StackMass_Landed	4974.37	4971.54	0.1%
y8	OMSPropMass_Landing	926.94	926.34	0.1%
y9	RCSPropMass_Landing	60.23	60.18	0.1%
y10	RCSPropMass_ACEntry	332.77	332.71	0.0%
y11	T2Winit_MDS_EarthG	1.4023	1.4023	0.0%
y12	EngineVacuumIsp_DS	338.30	338.30	0.0%
y13	EngineExitDiameter_DS	0.8014	0.8008	0.1%
y14	EngineLength_DS	1.5677	1.5643	0.2%
y15	ThrustPerEngine_DS	4609.22	4604.89	0.1%
y16	JettMass_PostCapture	0.00	0.00	#DIV/0!
y17	JettMass_PreDOI	221.14	221.15	0.0%
y18	JettMass_PostEntry	600.99	684.47	-12.2%

Pump-fed NTO/MMH Calibration Engine

EDL-SA

RS-72 - Windows Internet Explorer

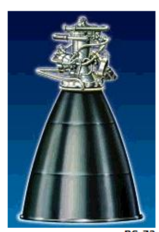
http://www.astronautix.com/engines/rs72.htm

Ads by Google | Engine | F Rocket Engine | Gas Turbine Engine | Mapa RS | Motor Bike Engine

RS-72

Rocketdyne, Ottobrunn N2O4/MMH rocket engine. 55.4 kN. Isp=340s. Aestus engine enhanced with the addition of a Boeing-Rocketdyne XLR 32 turbo-pump.

Dasa (Germany)/Rocketdyne Upper Stage. Gas generator, pump-fed. The RS 72 was a bipropellant turbopump rocket engine developed by Ottobrunn together with Boeing-Rocketdyne. The RS 72 was based on the Aestus engine used on the Ariane 5 upper stage. Performance was enhanced with the addition of a Boeing-Rocketdyne XLR 32 turbo-pump.



RS-72
Credit: Boeing / Rocketdyne

Engine: 138 kg (304 lb). *Chamber Pressure:* 60.00 bar. *Area Ratio:* 300.

Height: 2.29 m (7.50 ft).
Diameter: 1.30 m (4.20 ft).
Thrust: 55.40 kN (12,454 lbf).
Specific impulse: 340 s.
Vague: 1999.

EDL-SA

6.1.2 EDL-SA HIAD (65 degree Sphere Cone) Ablator Mass Model Summary

Al Covington
Dave Kinney
Kathy McGuire
Jim Arnold

Objectives and Outline

(Jim Arnold)

EDL-SA

Objective or Task:

1. **Develop engineering fidelity math models for aerothermodynamics and flexible ablators**
2. **Support sizing/mass estimate trade studies for a variety of HIAD designs**
3. **Provide flexible ablative MERs for architecture studies**

Outline:

1. **Dual HIAD and Single (dual pulse) HIAD Sizing, Mass Estimates Results and MER for ablative TPS (Spot checks for direct entry/ completed); If needed those MERs will be completed in the next two weeks)**
   - **Environments**
   - **TPS Sizing Stacks**
   - **Sizing Results**
   - **MERs**
2. **Math model basis and assumptions, recent flexible TPS test results and comparisons**
3. **Response to EDL-SA PM's request for substantial information on flexible ablator development and major issues that must be solved prior to an EFF vehicle PDR using this technology**
4. **Concluding Remarks**

Summary:

- Tasks mainly completed: Most MER's developed and mass estimates provided for Flexible PICA and SIRCA with and without Qfelt insulation layer.
  - Flexible ablators can survive environments for <u>all</u> EFF HIAD designs including high speed direct entry
  - SIRCA flex TPS masses are comparable to AFRSI for the benign environments (out-of-orbit entry case)
- The recent arc jet test data of flexible PICA and SIRCA tests and comparisons are promising

PICA-flex and SIRCA-flex

(Jim Arnold)

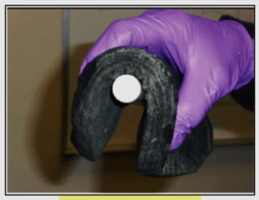
EDL-SA

Rigid Ablators
- Phenolic Impregnated Ceramic Ablator (PICA)
- Silicone Impregnated Reusable Ceramic Ablator (SIRCA)

Flexible Ablators

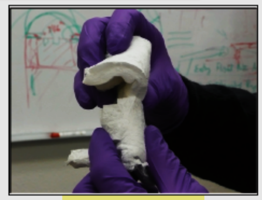
Substrate/reinforcement	+	Matrix	=	*Flexible* Ablator
Flexible Felt [silica] [carbon]	+	Resin* [silicone] [phenolic]	=	TPS [SIRCA-flex] [PICA-flex]

*resin is mainly responsible for the pyrolysis process



PICA-flex

POC: Jim Arnold/NASA Ames
See Poster by M. Stackpoole



SIRCA-flex

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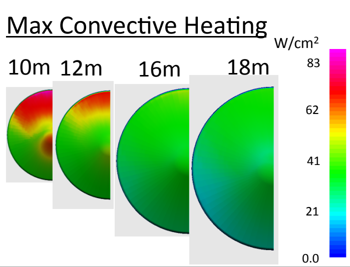
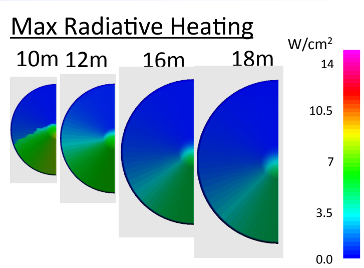
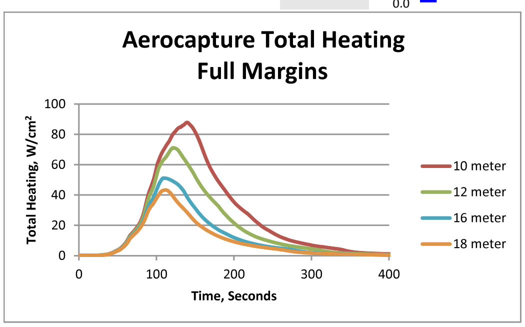
HIAD Heating – Aerocapture (7.36 km/s)

(D. Kinney & K. McGuire)

EDL-SA







(See more plots/details in back-up)

HIAD Heating – Entry (3.5 km/s)

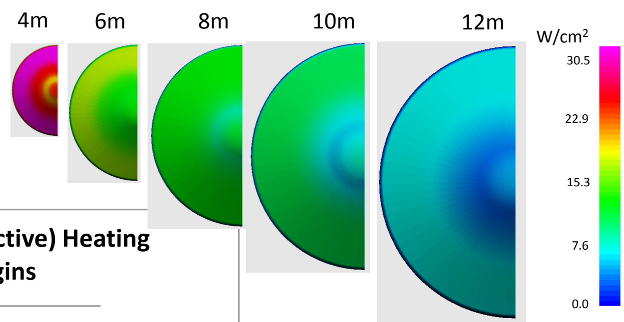
(D. Kinney & K. McGuire)

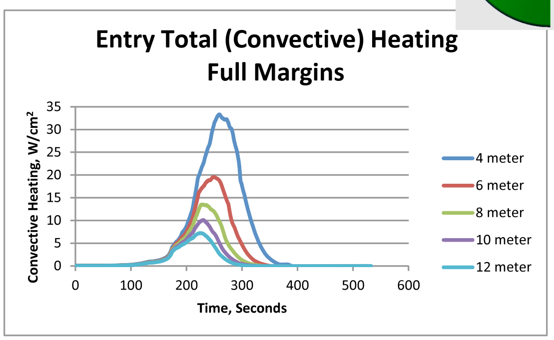
EDL-SA

Essentially no radiative heating

Max temperature for 4 meter case is 1610 Kelvin (2440 °F)

Max Convective Heating

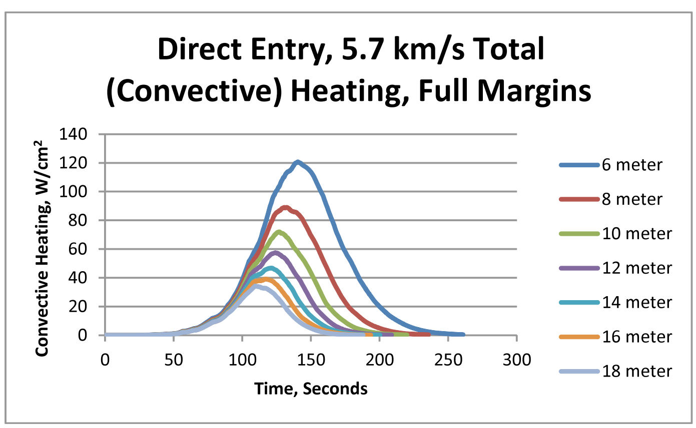




HIAD Heating – Direct Entry (5.7 km/s)

(D. Kinney & K. McGuire)

EDL-SA

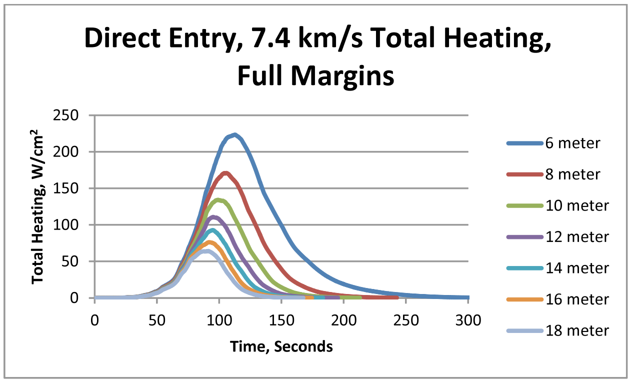


No radiative heating

HIAD Heating – Direct Entry (7.4 km/s)

(D. Kinney & K. McGuire)

EDL-SA



Environment Margins

(K. McGuire)

EDL-SA

From Mars EDL-SA Thermal Protection System (TPS) Margin Management Plan, V2, June 9, 2009

Aerothermal database	Turbulent
Aerothermal Laminar Convective Uncertainty	1.2
Aerothermal Turbulent Convective Uncertainty	1.35
Aerothermal Radiative Uncertainty	1.6
Trajectory Dispersion Factor – Convective Heat Rate	1.1
Trajectory Dispersion Factor – Convective Heat Load	1.2
Trajectory Dispersion Factor – Radiative Heat Rate	1.5
Trajectory Dispersion Factor – Radiative Heat Load	1.2

Estimated Thermal Properties for SIRCA -flex

EDL-SA

Reference: TPSX

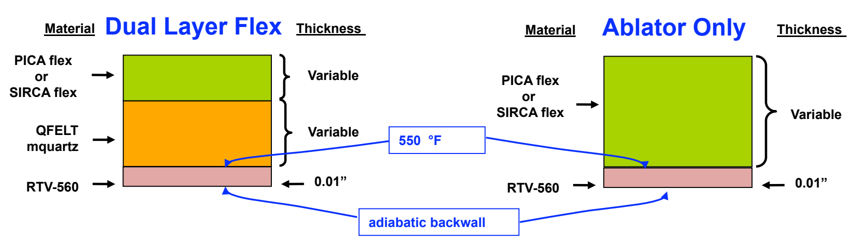
- Properties based on published results for TRL 9 SIRCA-15 (15 lb/ft^3) and fiber/Silicone ratios, except virgin density assumed to be 10 lb/ft^3
- Char density = 8 lb/ft^3
- Thermal conductivity 80 percent SIRCA-15
- Silicone decomposition same as SIRCA-15
- Virgin and char emissivity same as SIRCA-15
- Q-Felt properties based on published TRL 9 data
- Similar assumptions for PICA-flex based on CEV PICA data

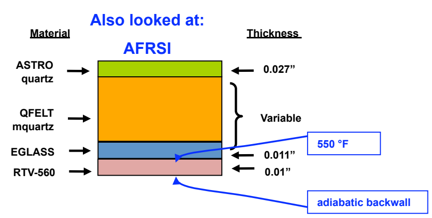
A. Covington/ARC

TPS Sizing Material Stacks

EDL-SA

(K. McGuire)





TPS Sizing Assumptions

(K. McGuire)

EDL-SA

Tools CBAERO 3.5.0, TPSSizer 3.3.2, FIAT 2.6.1, CBAERO

Sizing methodology used by the CEV TPS ADP and currently being used by Orion TPS I/O.

From Mars EDL/SA Thermal Protection System (TPS) Margin Management Plan, V2, June 9, 2009

Initial Temperature*	**10 ºF**
Radiation Sink Temperature*	**70 ºF**
Allowable Bondline Temperature	**550 ºF**
Blowing Factor	**0.4**
Ablator Fail Lien	**50%**
Thermal Margin	**108 ºF**
Default FOS	**1.1**

Notes:

* For Dual Pulse HIAD analysis - after aerocapture, the temperature during cool-off returns to the 70 ºF radiation sink temperature, not the original 10 ºF initial temperature

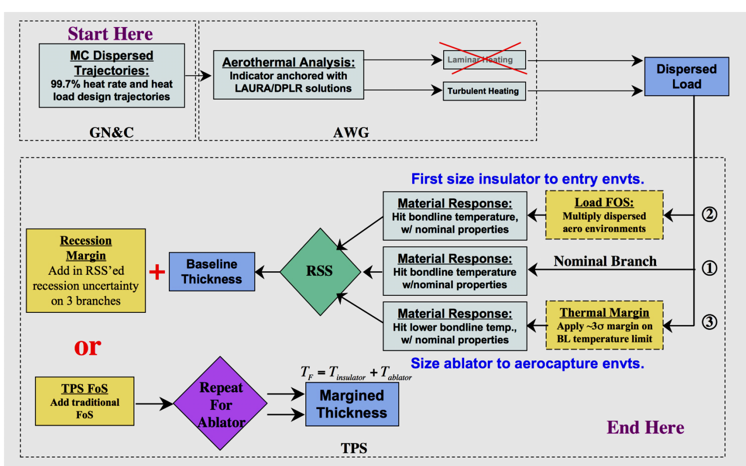
TPS Sizing Process

(K. McGuire)

EDL-SA

From Mars EDL-SA Thermal Protection System (TPS) Margin Management Plan, V2, June 9, 2009

For the HIAD cases this process results in sized results which are 35-70% heavier than the completely unmargined results.



Dual HIAD TPS Sizing Results

(K. McGuire)

EDL-SA

Diameter meters	Official Results / Full Body Results: TPS Material	TPS Mass kg	RTV Mass kg	Total TPS System Mass kg	Half Body Results: Area m2	SiSi TPS kg	SiSi_Qfelt TPS kg	CfeltPh TPS kg	CfeltPh_Qfelt TPS kg	AFRSI TPS kg
Entry Only HIAD										
6	SiSi_Qfelt	106.62	11.64	**118**	16.25	61.36	53.31	72.29	59.62	50.2
8	CfeltPh_Qfelt	158.66	20.69	**179**	28.89	97.39	80.24	114.4	79.33	76.77
8.5	CfeltPh_Qfelt	166.16	23.35	**190**	32.61	106.1	87.52	126	83.08	81.68
10	CfeltPh_Qfelt	198.66	32.32	**231**	45.13	131.4	109.6	163.3	99.33	103
12	CfeltPh_Qfelt	252.20	46.54	**299**	64.99	167.1	140.6	218.2	126.1	133
Aerocapture Only HIAD										
10	SiSi_Qfelt	449.80	32.32	**482**	45.13	273.9	224.9	390.1	341.8	
12	SiSi_Qfelt	603.40	46.54	**650**	64.99	372.7	301.7	480.7	387.8	
13.5	SiSi_Qfelt	730.20	58.90	**789**	82.25	454	365.1	559	428.5	
16	SiSi_Qfelt	1073.60	82.71	**1156**	115.5	617.1	536.8	744.3	536.8	
18	SiSi_Qfelt	1191.40	104.69	**1296**	146.2	755.7	595.7	904.8	621.1	

lowest mas lowest mass case
case used case used in MER

- The (SIRCA+Qfelt) system mass estimates are comparable to AFRSI estimates for entry only cases.
- The PICA with Qfelt is comparable to but slightly higher than the (SIRCA+Qfelt) system mass for Aerocapture.
- In terms of heat flux capability - (PICA Flex > SIRCA Flex > AFRSI)

Single HIAD (Dual Use) TPS Sizing Results

(K. McGuire)

EDL-SA

Diameter meters	Official Results / Full Body Results: TPS Material	TPS Mass kg	RTV Mass kg	Total TPS System Mass kg	Half Body Results: Area m2	SiSi_Qfelt TPS kg	CfeltPh_Qfelt TPS kg
Entry + Aerocapture Dual Use HIAD							
8.5	SiSi_Qfelt	256.60	23.35	**280**	32.61	128.3	159.7
10	SiSi_Qfelt	411.00	32.32	**443**	45.13	205.5	332.5
12	SiSi_Qfelt	698.20	46.54	**745**	64.99	349.1	395

lowest mass case
case used in MER

- The (SIRCA+Qfelt) system mass estimates are lower than the (PICA +Qfelt) system
- In terms of heat flux capability - (PICA Flex > SIRCA Flex)

Direct Entry HIAD TPS Sizing Results

(K. McGuire)

EDL-SA

Diameter meters	Official Results / Full Body Results: TPS Material	TPS Mass kg	RTV Mass kg	**Total TPS System Mass kg**	Half Body Results: Area m2	SiSi TPS kg	SiSi_Qfelt TPS kg	CfeltPh TPS kg	CfeltPh_Qfelt TPS kg
Direct Entry 5.7 km/s									
6	SiSi_Qfelt	114.70	11.64	**126**	16.25	57.96	57.35	147.9	144.8
8	SiSi_Qfelt	180.84	20.69	**202**	28.89	92.98	90.42	176.2	170.9
10	SiSi_Qfelt	258.40	32.32	**291**	45.13	134.5	129.2	216.2	203.4
12	SiSi_Qfelt	345.20	46.54	**392**	64.99	181.9	172.6	267.9	240.6
14	SiSi_Qfelt	438.40	63.34	**502**	88.46	234.6	219.2	273.9	327.5
16	SiSi_Qfelt	539.40	82.71	**622**	115.5	292	269.7	397.8	303.8
18	SiSi_Qfelt	649.40	104.69	**754**	146.2	354.2	324.7	481	348.4
Direct Entry 7.4 km/s									
6	CfeltPh	361.00	11.64	**373**	16.25	73.06	73.48	180.5	208.1
8	CfeltPh_Qfelt	449.40	20.69	**470**	28.89	105.4	102	232.6	224.7
10	CfeltPh_Qfelt	504.40	32.32	**537**	45.13	147.8	141.8	263.5	252.2
12	SiSi_Qfelt	375.60	46.54	**422**	64.99	196.6	187.8	308.4	289.2
14	SiSi_Qfelt	476.20	63.34	**540**	88.46	251.2	238.1	366	323.5
16	SiSi_Qfelt	585.40	82.71	**668**	115.5	311.1	292.7	432.3	352.6
18	SiSi_Qfelt	702.00	104.69	**807**	146.2	376.4	351	507.2	402.8

lowest mass case

case used in MER

- For the smaller diameter (6-10m) cases of the 7.4 km/s direct entry, the heating rates are greater than the expected 115 W/cm² material limit for SIRCA-flex. For those cases, the higher mass PICA-flex is used.

Dual HIAD TPS MER

(D. Kinney) – other MERs are in back-up

EDL-SA

For Si/Si/Qfelt bonded with RTV to the structure.

$$M_{AC} = 1.850 \times Q_{AC}^{0.2803} \times S_{ref} \quad \text{kg}$$

$$M_E = 1.850 \times Q_E^{0.2803} \times S_{ref} \quad \text{kg}$$

$$M_{total} = M_{AC} + M_E \quad \text{kg}$$

$$Q_{AC,E} = \int \dot{q}_{AC,E}\, dt \quad \text{MJ/m}^2$$

$$S_{ref} = \frac{\pi \times D^2}{4} \quad \text{m}^2$$

Where Q must be in MJ/m^2. Please note the heating rate estimate from the HIAD database is in W/cm^2.

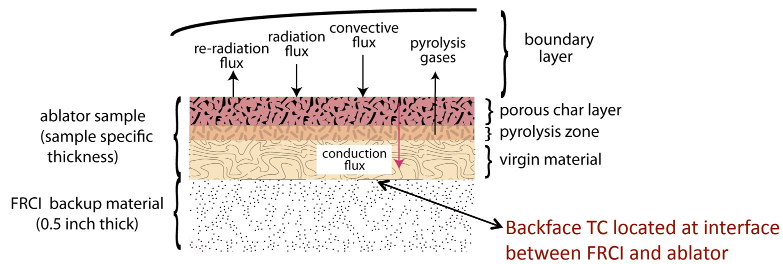
AC = Aerocapture; E = Entry;

Total is Dual heating of Aerocapture followed by Entry

EDL TDP Ablator Screening Tests

EDL TDP

(Al Covington)

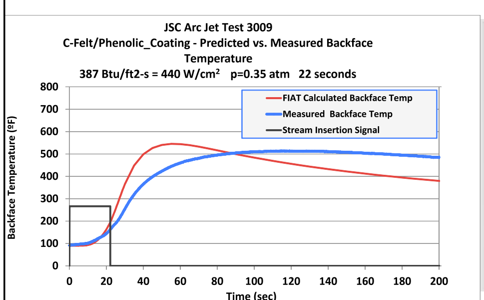


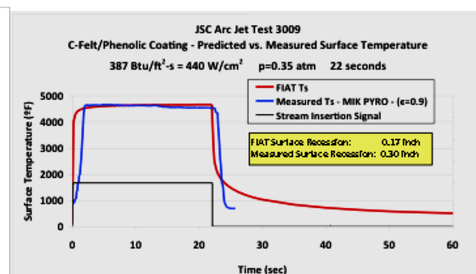
- **Published PICA and SIRCA thermophysical properties used for PICA-Flex and SIRCA-Flex models and adjusted for sample densities (measured compositions & properties not available yet)**
  - **PICA-Flex virgin density≈14 lb/ft³ (Std. PICA density=15 lb/ft³)**
  - **SIRCA-Flex virgin density≈19 lb/ft³ (Std. SIRCA-15 density=15 lb/ft³)**
- **Felt/resin ratio assumed same as for PICA and for SIRCA-15 (questionable assumption)**
- **Average stagnation region heating rate: 83% of stagnation centerline based on calorimetry**
- **FIAT code used for thermal and ablation response predictions**

EDL TDP Ablator Screening Tests

EDL TDP

PICA-Flex Arc Jet Test Results (Al Covington)





Preliminary Results – PICA-Flex (Carbon Fibers/Phenolic Coated)

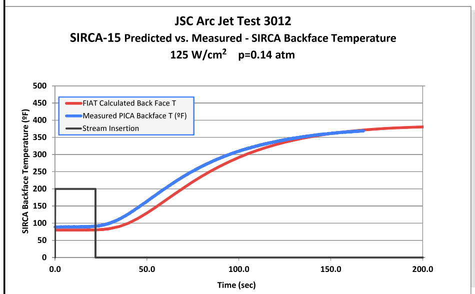
Note: Average stagnation region heating rate used (83% of stagnation centerline)

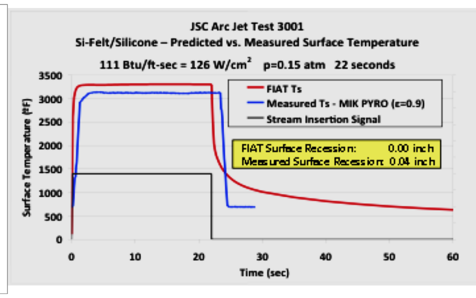
- Surface recession discrepancy may be due to different PICA-Flex and PICA fiber/resin ratios
- Evidence of side-wall thermal effects with water-cooled holder
- Improved agreement expected for future arc jet tests with use of measured new ablator material property data and better model design

EDL TDP Ablator Screening Tests

SIRCA-Flex Arc Jet Test Results (Al Covington)

EDL TDP





Preliminary Results – SIRCA-Flex (Silica Fibers/Silicone Polymer)

Average stagnation region heating rate used (83% of stagnation centerline)

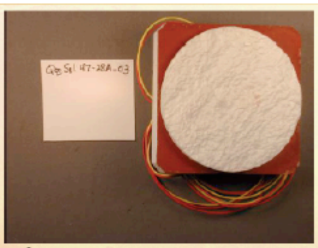
- Reasonable surface recession agreement
- Surface temperature discrepancy (~ 150 ^{O}F) may be due to the char emissivity difference (< 0.9?)
- Evidence of side-wall thermal losses to water-cooled holder (i.e., low backface temperature)
- Improved agreement expected for future arc jet tests with use of measured new ablator material property data and better model design

SIRCA-Flex LHMEL Screening Testing

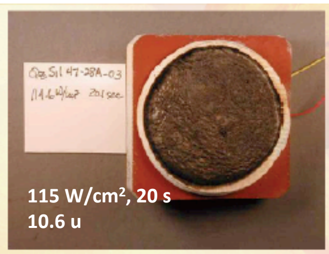
(Susan White)

EDL TDP

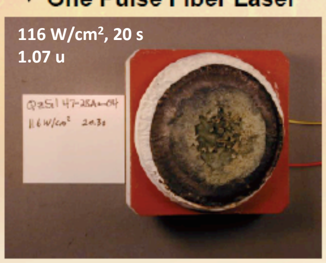
Model Pre-Test



One Pulse → CO2 Laser

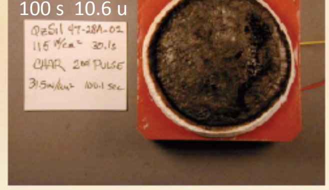


↓ One Pulse Fiber Laser



↓ 2nd Pulse CO2 Laser

115 W/cm², 30 s + 31.5 W/cm² for 100 s 10.6 u



Caution: 1.07 Transparency and CO_2 S/L IR radiation may be an Issue

Conclusions from Screening Tests

(Al Covington/Jim Arnold)

EDL TDP

- Arcjet data prove SIRCA-flex is a viable candidate for dual heat pulse and aerocapture only HIAD applications for 1st pulse heat rates up to ~ 115 W/cm2
- LHMEL testing suggests that SIRCA- flex and PICA-flex are capable of dual heat pulse performance
- Arcjet data prove PICA-flex is a viable candidate for much higher heating rates (~ 400 W/cm2) allowing for smaller flexible heat shields and more aggressive entry environments
- Ongoing analysis and improved arcjet model design will improve the understanding of the flexible ablator performance

Response to PM's Request for IPR

(J. Arnold)

EDL-SA

Request: "Provide substantive information to enable the EFF IPR panel to assess the credibility and uncertainty associated with the TPS Model"

Notes:

- Ablator TPS analysis for EFF closely follows that done for the 2009/2010 EDL-SA Exploration efforts.

- Credibility metrics for a technology in development: People & their tools, facilities & processes they use and their track record. The mulit-center, multi-generational flex ablator group: involves people that: Developed flown TRL 9 PICA, SIRCA, Shuttle tiles, AFRSI etc. Conceived, sized and validated peer reviewed rigid, dual heat pulse, dual layer TPS for the Mid L/D EDL - SA vehicle. Conceived flexible ablators enabling the EDL-SA study the of 23 meter HIAD. Flexible ablator group uses industry standard tools (FIAT, DPLR, CBAERO) and processes (e.g., margins policies for ablator development). These tools or processes were developed by the group members or their close associates. While piecewise testing is used for ablator development, tried and true arcjet test data closely simulated flight environments is demanded for thermal response modeling that directly impacts mass estimates.

"Concise description of the process used to generate the model and TPS mass uncertainties"

- **Aerothermal environments: charts 4 – 8.**
- **Sources of data used in flexible ablator models: Chart 9.**
- **Process for TPS Sizing and margins: Charts 9-15.**
- **Margins relate to mass uncertainties from 35 –70 % depending on the flight case: Chart 9. Additionally, there is the blanket 1.495 factor accounting for the low TRL of flexible ablators. Focus to date has been on materials development, their thermal performance and stow-ability. System level functions will be evaluated in future ETDD research. System level mass hits remain to be scoped.**
- **MERs based on CEV-type TPS margins and margined heat loads: Chart 16 and backup**

Response to PM's Request for IPR
(J. Arnold)

EDL-SA

"Major issues that would need to be resolved before a PDR (TRL 6) for an EFF Mars mission (for the heat rates and loads for Mars aerocapture and/or entry)"

- Programmatic; **Based on the current ETDD planning and the OCT EDL Roadmap, TRL 6 versions of PICA-flex and SIRCA-Flex will be available by ~ 2018 that would meet the needs for an EFF mission. These ablators also would have the cross capability specified in the OCT EDL roadmap to meet other needs, e.g., solutions to the issues with tiled PICA that plagued the Orion TPS ADP, affordable TPS for COTS vendors and a 23 meter Exploration class HIAD. However, based on recent track records, in is unclear that requisite arcjet testing necessary for flexible ablator development will be available. If mission pull for an EFF vehicle with ablatative TPS arose, we estimate that TRL 6 flexible ablators could be available in ~ 3 ½ years.**

- Technical: **TC stacks for flexible TPS represent a challenge. A joint HIAD/ETDD team is addressing this instrumentation development need for ground and flight testing . This partnership can be expanded to efficiently address system level issues that may be encountered for flexible ablator applications. KPPs and TRL exit criteria have been developed for flexible TPS and they apply to both insulating and ablating TPS.**

Summary and Recommendations
(J. Arnold)

EDL TDP

- **Preliminary flexible ablative TPS material thermal response models for SIRCA-flex and PICA-flex have been developed**
- **TPS sizing performed for all EFF HIAD cases**
- **All MERs except for hyperbolic entry were generated and provided for system studies**
- **Screening testing results indicate SIRCA-flex to be a viable candidate for most dual heat-pulse, aerocapture and direct entry HIAD applications. PICA-flex enables 7.4 km/s hyperbolic entry for smaller EFF HIADs**
  - **Ablative flexible TPS screening tests show that both SIRCA-flex as well as PICA-flex are viable candidates for EFF HIADs**
    - **SIRCA-flex ~ 115 W/cm^2 and PICA-Flex ~ 400 W/cm^2**
    - **LHMEL testing suggests that <u>all</u> flexible TPS ablators are dual heat pulse capable (three PICA-flex and 6 SIRCA-flex "cousins")**
- **Recommendation: Future system studies should consider smaller diameter HIADs accounting for shear layer impingement on payload**

Backup

EDL-SA

Notes For MER Development

EDL-SA

- All heat loads based on heat rate indicator previously provided for 65° sphere cone geometry.
- Standard TPS and aerothermal margins applied.
- No weight growth allowances applied to TPS masses provided.

Dual HIAD TPS MER

(D. Kinney)

EDL-SA

For Si/Si/Qfelt bonded with RTV to the structure.

$$M_{AC} = 1.850 \times Q_{AC}^{0.2803} \times S_{ref} \quad \text{kg}$$

$$M_E = 1.850 \times Q_E^{0.2803} \times S_{ref} \quad \text{kg}$$

$$M_{total} = M_{AC} + M_E \quad \text{kg}$$

$$Q_{AC,E} = \int \dot{q}_{AC,E}\, dt \quad \text{MJ/m}^2$$

$$S_{ref} = \frac{\pi \times D^2}{4} \quad \text{m}^2$$

Where Q must be in MJ/m^2. Please note the heating rate estimate from the HIAD database is in W/cm^2.

AC = Aerocapture; E = Entry;

Total is Dual heating of Aerocapture followed by Entry

Dual HIAD TPS MER Example

(D. Kinney)

EDL-SA

Entry with 8.5 meter HIAD:

Trajectory: EFF_EDLRef_TPStraj_10.txt

$$S_{ref} = 56.75 \quad \text{m}^2$$

$$Q_E = 8.010 \quad \text{MJ/m}^2$$

$$M_E = 188.1 \quad \text{kg}$$

Aerocapture with 13.5 meter HIAD:

EFF_AerocapRef_TPStraj_11.txt

$$S_{ref} = 143.14 \quad \text{m}^2$$

$$Q_E = 45.490 \quad \text{MJ/m}^2$$

$$M_E = 772.04 \quad \text{kg}$$

Single HIAD (Dual Use) TPS Sizing MER
(D. Kinney)

EDL-SA

$$M_{Total} = 2.140 \times Q_{Total}^{0.2803} \times S_{ref} \quad \text{kg}$$

$$Q_{Total} = Q_{AC} + Q_{E} \quad \text{MJ/m}^2$$

$$Q_{AC,E} = \int \dot{q}_{AC,E}\, dt \quad \text{MJ/m}^2$$

$$S_{ref} = \frac{\pi \times D^2}{4} \quad \text{m}^2$$

Where Q must be in MJ/m^2. Please note the heating rate estimate from the HIAD database is in W/cm^2.

Single HIAD (Dual Use) TPS MER Example (D. Kinney)

EDL-SA

Aerocapture and Entry with 12.0 meter HIAD:
EFF_AerocapRef_TPStraj_8.txt
EFF_EDLRef_TPStraj_1HIAD_17.txt

$$S_{ref} = 113.10 \quad \text{m}^2$$

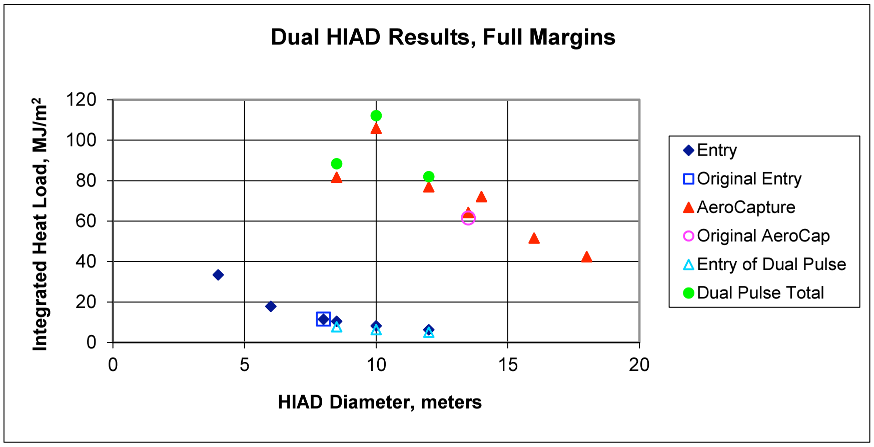
$$Q_{E} = 56.239 + 3.910 = 60.150 \quad \text{MJ/m}^2$$

$$M_{E} = 763.12 \quad \text{kg}$$

Integrated Heatload

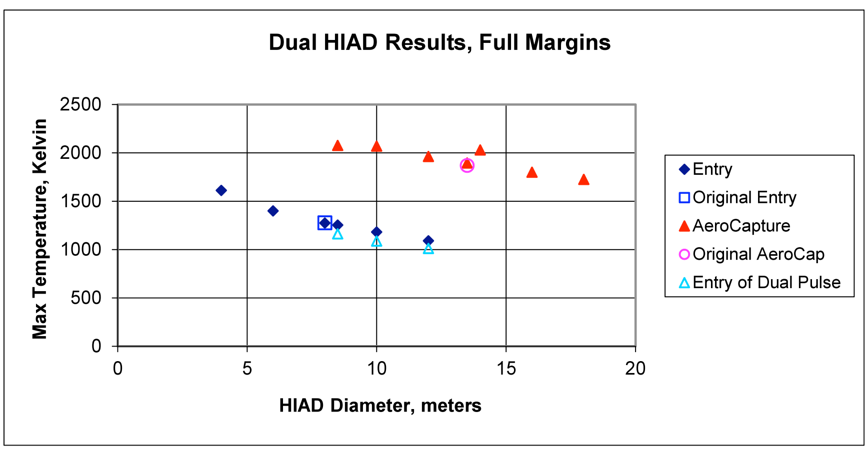
(K. McGuire)

EDL-SA



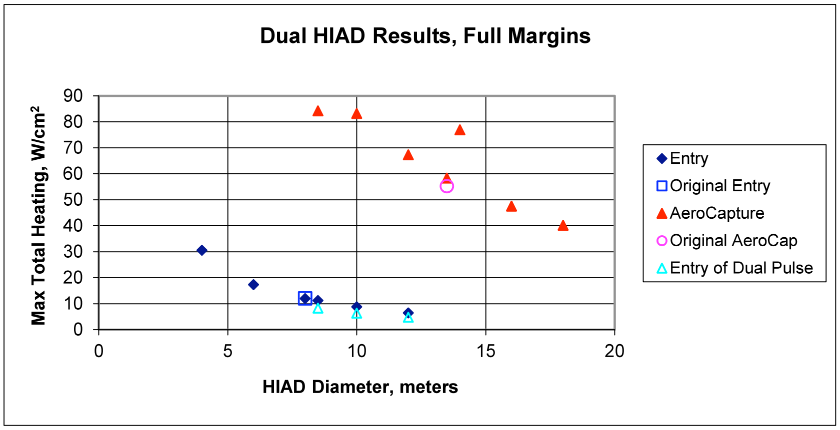
Max Surface Temperature (Radiation Equilibrium) (K. McGuire)

EDL-SA



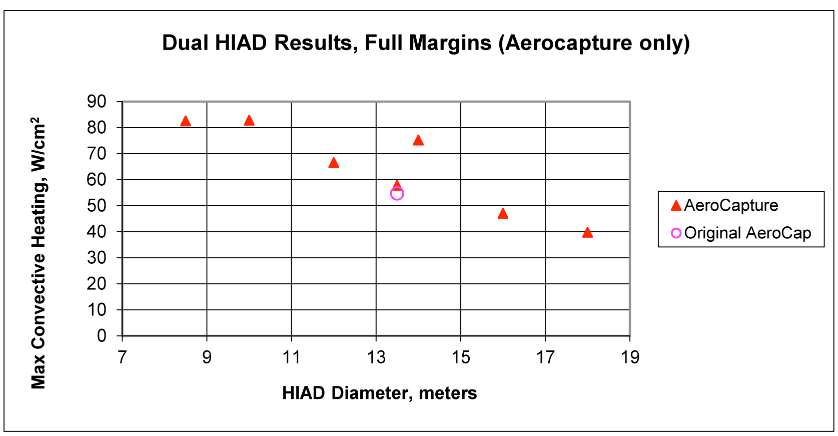
Max Total Heating
(K. McGuire)

EDL-SA



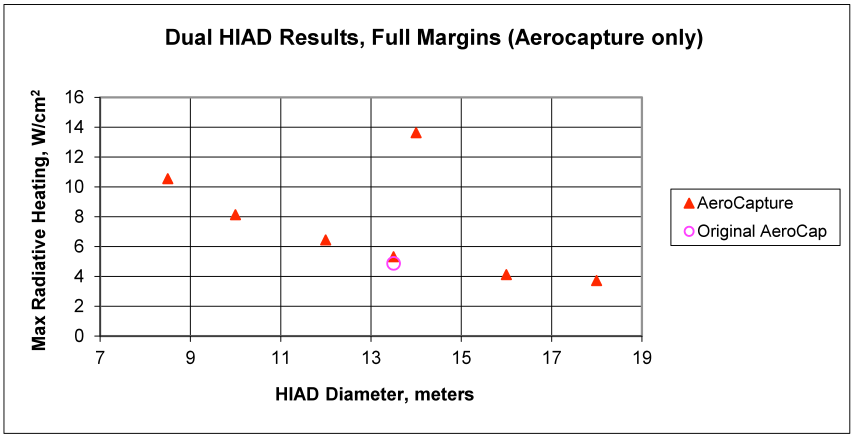
Max Convective Heating Aerocapture (K. McGuire)

EDL-SA



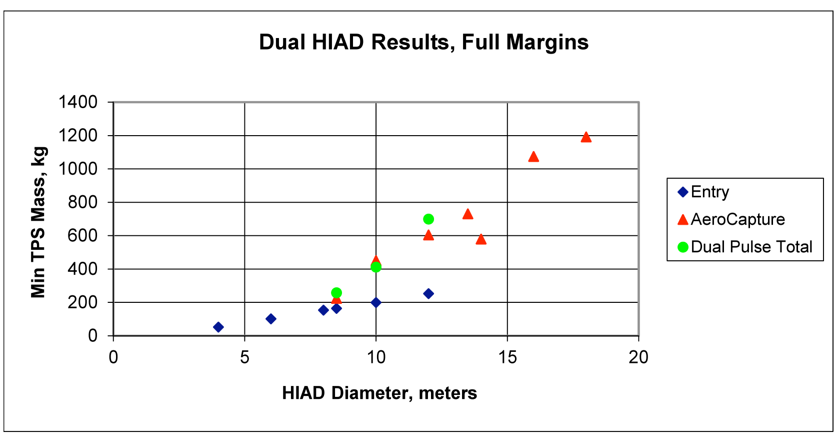
Max Radiative Heating Aerocapture (K. McGuire)

EDL-SA



Min Ablative TPS Mass (K. McGuire)

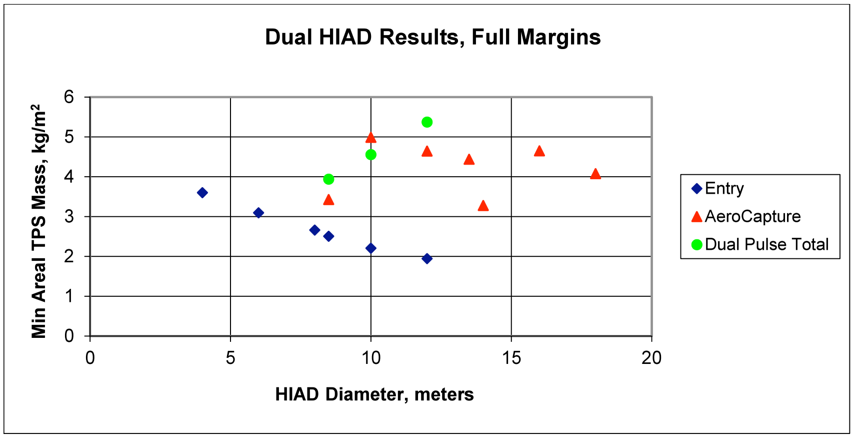
EDL-SA



Min Ablative TPS, Areal Mass

(K. McGuire)

EDL-SA



Response to PM's Request for IPR

(J. Arnold)

EDL-SA

Request: Provide substantive information to enable the panel to assess the credibility and uncertainty associated with the TPS Model

- **Estimated uncertainty in the resulting TPS mass prediction**
  - **TPS material property uncertainties in current approach are accounted for by application of CEV best practices margins policy: charts 11 &12. Future MERs: Same process, with updated materials properties and ablator performance using data from planned ETDD TRL advancements**
  - **Viability of SIRCA-flex (up to 115 W/cm^2) and PICA-flex materials (up to 400 W/cm^2) HIAD shown by arcjet testing. Dual heat pulse capability shown by LHMEL screening tests: charts 10-15**
  - **ELD TDP/ETDD team already has considerably improved flexible ablative material processes in hand. Lighter, higher performance ablative materials are anticipated from our program in FY 11**
  - **Based on ETDD flex ablator team's unique experience (ablatives and shuttle Flexible TPS) brings credibility to provide PICA-flex and SIRCA-flex ablative materials**

EDL-SA

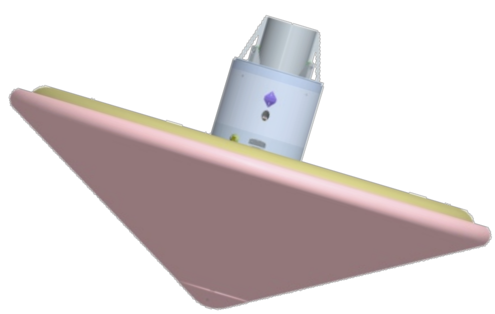
6.1.3 Insulative Flexible TPS

Joe Del Corso

EDL-SA

Overview

- **General Aeroshell**
  - Requirements
  - Approach
  - Materials Selection
- **Thermal Model**
  - Baseline TPS
  - Materials Overview
- **Ground Tests Overview**
  - TPS Performance Results
- **EDL-SA**
  - Mass Model
  - Caveats
  - Model Uncertainties
- **Deployable TPS**
  - KPP
  - Technology/TRL Status



Requirements of Flexible TPS

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- Demonstrate margined performance at entry aerothermal environments
- Pack aeroshell to high densities (~25lb/ft3)
- Fold materials to near-zero bend radius (hard crease) without degradation of aeroshell performance
- Deploy after long duration storage at high packing densities without significantly changing thermal physical characteristics
- Model and reliably predict material performance, and be able to size TPS for desired effect

Flexible TPS Approach

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Heavy emphasis on modular design approach
- Allows design to swap out any component with more capable materials and allows tailoring of TPS to mission requirements

Engineering functional aspects
- Outer layers
  - Aerothermal environments
  - Reduce or eliminate hot gas impingement
- Insulators
  - Manage integrated heat load
- Gas barrier
  - Eliminate potential for hot gas inflow through materials
- Structural layers
  - Support structural loads at bond line temperatures

Material Selection Considerations

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- **Desired Material Characteristics**
  - **Low Areal Weight**
  - **Low Permeability**
  - **Fabric and Layup Malleability**
  - **Thermal Characteristics**
    - **High temperature capable**
    - **Low thermal transport (insulator)**
    - **High emissivity (outer fabric)**
    - **Low catalycity**
  - **Sustained performance after handling**
  - **Rebound to original shape after compression**
  - **Material uniformity/homogeneity even after packing**

TPS Thermal Model

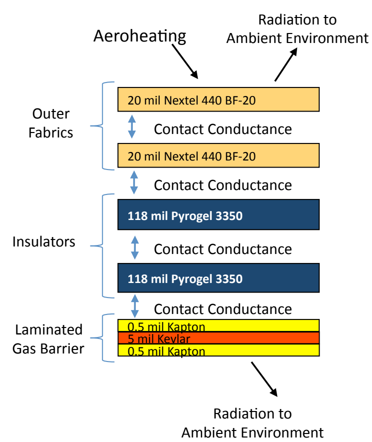
EDL-SA

Current 1D diffusion thermal model

- Contact conductance from AIRS study
  - Analysis being updated in HIADS Flexible TPS ground effort
- Sizing TPS for trajectory, varies number of insulation layers
  - Assume stagnation heating across aeroshell
- Evaluating updated, more robust physics model

Max cont. use temperatures:
Nextel BF-20 = 1370°C
Pyrogel 3350 = 1100°C*
Laminate = 350°C

* Single use temperature



Baseline TPS

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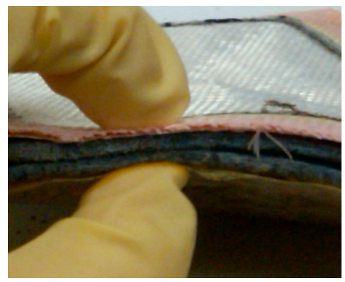
Outer Fabrics
- 20 mil Nextel 440 BF-20
- 20 mil Nextel 440 BF-20

Insulators
- 118 mil Pyrogel 3350
- 118 mil Pyrogel 3350

Laminated Gas Barrier
- 0.5 mil Kapton
- 5 mil Kevlar
- 0.5 mil Kapton



Baseline TPS: Nextel BF-20

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3M Product

- Nextel Ceramic Fibers 440
  - Aluminoborosilicate containing mullite crystals
  - Retain strength at continuous use temperatures of 1370°C (2500°F)
  - Threads are coated in polymer to prevent abrasion damage
    - Polymer off-gasses when heated to ~150-200°C
    - Very low mass application is removed within seconds of exceeding the allowable temperature
  - Material properties
    - LM-TPRL
    - Manufacturer spec

Baseline TPS: Pyrogel 3350

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Aspen Aerogel product

- Pyrogel 3350 is a 3mm thick OPAN batting impregnated with amorphous silica aerogel
  - OPAN – 70% oxidized polyacrilonitrile
  - Amorphous silica aerogel bonded to OPAN fibers
- Manufacturer spec sheet indicates max continuous use temperature of 350-400°C
  - 'continuous use' for material was measured in terms of 10-20 years
  - Single use temperatures capable of 1100°C for 5-10 minute durations*
- Off-gassing occurs between 400-800°C
  - TGA/FTIR indicate off-gassing products are
    - Residual H20, CO2, and hydrocarbon bonding agent byproducts of the manufacturing process
    - By 900°C Pyrogel 3350 in stable form
- Material Properties
  - LM-TPRL
  - GRC
  - Manufacturer spec

* George Gould, Director of Research and Development, Aspen Aerogel

Testing and Test Facilities

EDL-SA

- 8' High Temperature Tunnel (Winter 2007, Summer 2009)
  - Simulated mission heating rates and pressure conditions
  - Provides material and material lay-up screening tests
  - Aggressive load environment used to assess robustness
  - Calibrated initial thermal model used to evaluate flexible TPS
- LHMEL CO_2 Laser Heating (January 2010, September 2010)
  - Provides well controlled heating and environment conditions
  - Alternate heating used to exercise and improve thermal model
  - Used to test temperature failure limits of TPS materials
  - Excellent for cost-effective screening of material capability
- Arc-jet Panel Test Facility (July 2010)
  - Provides non-equilibrium chemistry conditions
  - Alternate heating used to exercise and improve thermal model
  - Used to test materials under high enthaply heating loads

Thermal Performance

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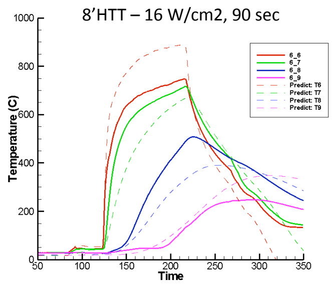
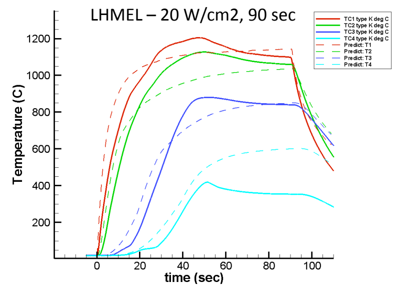
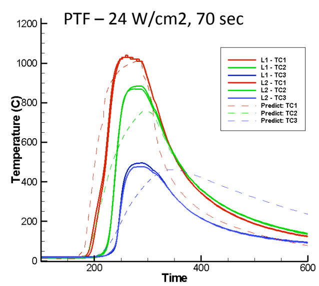




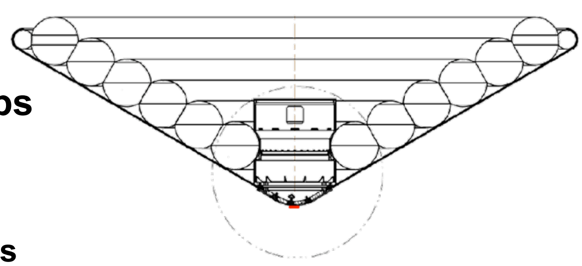


Mass Model

EDL-SA

Includes

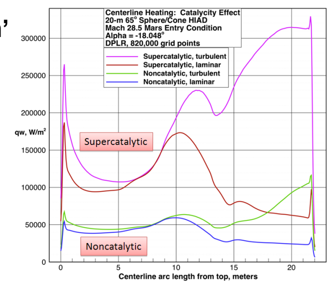
- Stacked Torus
- Stitching
- Retention straps
- TPS
  - Gas barrier
  - Insulator layers
  - Outer fabric layers



Mass Margins for EDL-SA (Conservatism)

EDL-SA

- Masses assumed 60° sphere-cone
  - Trajectories were run using 65° sphere-cone
    - Quick calculations indicate wetted areal mass dropped by 5-10% (trajectory/aeroshell diameter dependent)
- TPS based on IRVE-3 tested materials (more capable materials for all functions are under development)
  - Two outer fabrics
    - BF-20 -> SiC (lighter areal weight per layer ~16%)
  - Bondline temperatures constrained to <300°C
    - New materials can be taken to 500°C
- TPS includes 33% 'contingency mass margin'
- Reduce mass by optimizing torus diameters
  - Mass reduction of 10% possible
- Ames HR Indicator
  - Fully turbulent
  - Supercatalytic heating (low catalycity to be quantified)
  - Includes environmental uncertainties



Model Uncertainties

EDL-SA

- Extrapolation beyond two Pyrogel insulation layers
- Radiation slip through porous insulator
- Thermally induced changes to insulator
- Post handling, launch, and stowage performance
- Outer fabric optical properties
- Material catalysis

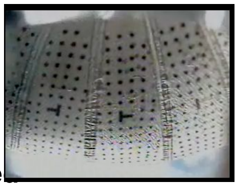
Deployable TPS
Key Performance Parameters

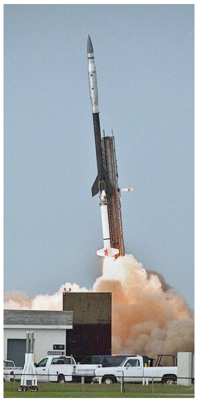
EDL-SA

- **Manufacturability:** Heat shield materials, subcomponents and assembly process have an envisioned capability of forming a half-scale deployable system based on previous demonstration at a geometrically relevant subscale.
- **Stow-ability:** When packed and stowed, heat shield system meets maximum allowable stowage volume without exceeding specified maximum dimensional constraints.
- **Operability:** Thermal protection system performance requirements, e.g., damage tolerance, handling, health monitoring, leakage, and repair-ability, have been clearly identified and engineering solutions established.
- **Deploy-ability:** Functionality of the thermal protection system is maintained following expected mission life cycle, e.g. assembly, pre-launch, launch, LEO loiter and space cruise to Mars during which the heat shield remains stowed in the folded state. (vibro-acoustic loading, out gassing, atomic oxygen effects, packing damage, contact sticking, etc.)
- *Planetary Protection: Capability of the TPS to be rendered "bug-free", meeting NASA's planetary protection requirements for Mars.*
- *Tolerance to MMOD damage: Capability of the TPS to function or be repaired after suffering MMOD damage in the LEO and Cruise environments.*
- **Material Processing Standards and Quality:** Heat shield materials and material constituents have an established pedigree, detailed written processing standards, and final quality inspection and acceptance criteria.

Current Technology Status

EDL-SA





- TPS
  - Aeroshell subassemblies fabricated, tested, and flown
  - Selected for IRVE-3 (18 W/cm2) and passed PDR
  - Experience working ground tests, IRVE, IRVE-II, and IRVE-3, and Orbital Flight Test
  - Engineering working details for
    - Fabrication and seams
    - Attachments
    - Inflation system
    - Stowage
    - Instrumentation
- Experienced team who have worked TPS (Rigid ablators, Hot structures, Flexible TPS)
  - Hyper-X (X-43A, X-37), Falcon, Shuttle
  - MEDLI (MSL), ICBM nosetip, missile interceptor TPS
  - Extensive experience with analysis methods and high-temperature (arc jet, laser, and vitiated) testing

TRL 3 Exit Criteria

EDL-SA

- **Written preliminary material specifications, processing, and acceptance standards.**
- **Basic constructs of required advanced analysis models have been established and are supported with property characterizations.**
- **Laboratory tests (no aerodynamic loading) on subcomponent, or "breadboard", assemblies have been performed.**
- **Analysis modeling maturity is sufficient to define a preliminary flight-like configuration and enable an empirical prediction of performance in a flight-relevant environment.**
- ***Functionality loss from extrinsic environmental effects including vacuum, atomic oxygen, and temperature are demonstrated.***
- ***Stowage and deployment requirements are developed and preliminary feasibility studies have been performed at subscale.***

TRL 4 Exit Criteria

EDL-SA

- **Potential issues of scalability have been identified, engineering solutions envisioned, and preliminary feasibility studies conducted.**
- **Analysis model maturity has demonstrated predictive agreement with measured ground tests of pristine materials within +/-20%.**
- ***Statistically significant set of ground tests simulating a proposed entry mission load cycle have been completed.***
- ***Stow and deployment tests have been completed to determine minimum standards for stowage and stowage volume together with defined heat shield durability limits against loss of functionality due to stowing process and mission storage time.***

TRL 5 Exit Criteria

EDL-SA

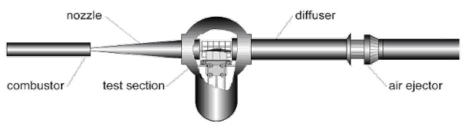
- **Large-scale manufacturing capability demonstrated at an engineering-relevant subscale.**
- **Mission cycle and peak heat flux tests on subcomponent assemblies with relevant OML manufacturing features completed and adequate residual functionality demonstrated.**
- ***Engineering design database established with statistically significant data samples sufficient to support SRR.***
- ***Relevant large-scale performance tests for stowage, deployment, and flight have been successfully performed.***
- ***Analysis model maturity has demonstrated predictive agreement with measured mission cycle testing of samples with surface features within +/-20%.***

EDL-SA

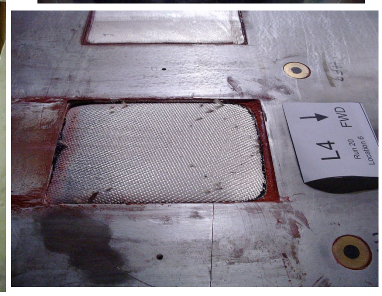
Backup

8-ft High Temperature Tunnel

EDL-SA

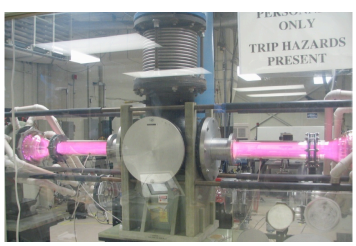


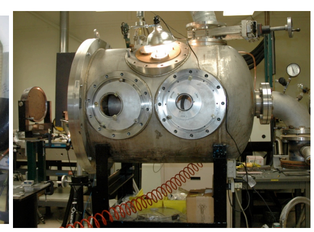
The 8-Foot High Temperature Tunnel (HTT) is a vitiated blow down tunnel capable of running Mach 3, 4, 5, or 7. The facility combustor adds energy to the flow by burning methane in air.

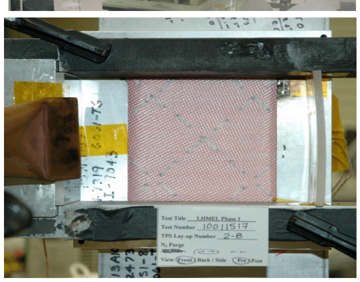


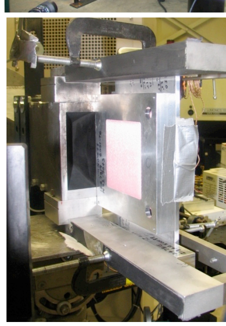
Laser-Hardened Materials Evaluation Laboratory LHMEL-I laser

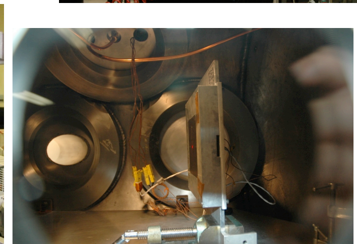
EDL-SA





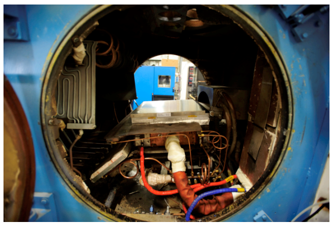


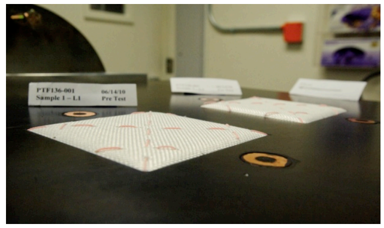


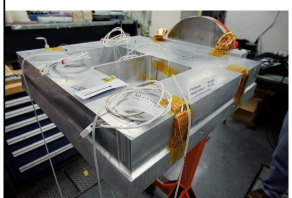


Panel Test Facility

EDL-SA

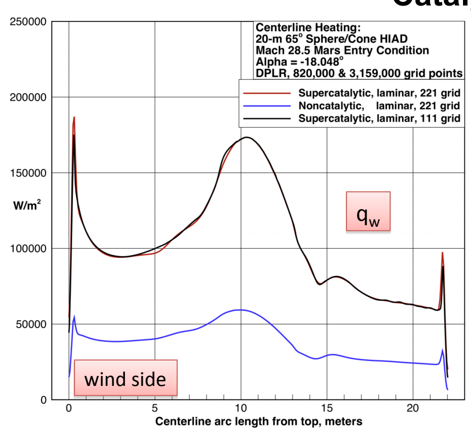


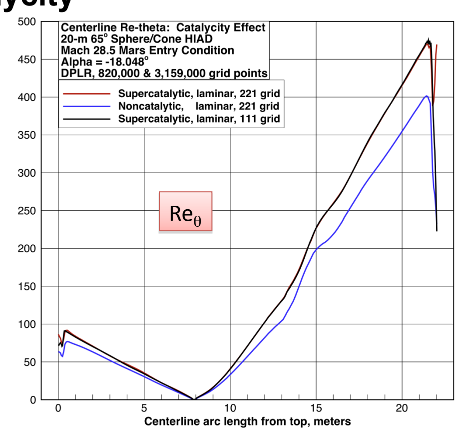




Laminar Centerline Heating and Re_θ: Effect of Surface Grid and Catalycity

EDL-SA

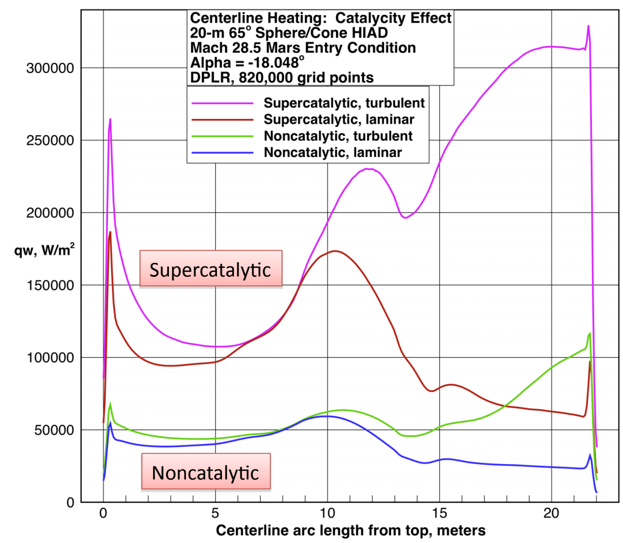




Coarser grid slightly overpredicts shoulder heating; adequate otherwise.
L/D varies between 0.250 and 0.254 across grids, catalycities, and flow type

Effect of Catalycity on Centerline Heating, Laminar & Turbulent

EDL-SA

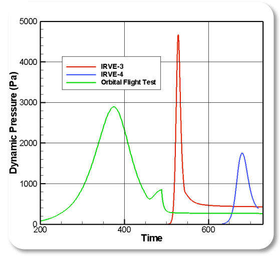


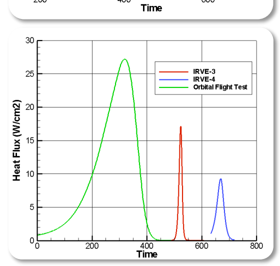
221 grid

EDL-SA

Test Facility Selection

Predicted Flight Environments





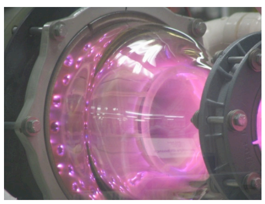
Test Conditions for Ground-Based Facilities

Facility	Sample Size (cm2)	Surface Pressure (kPa)	Heat Flux (W/cm2)	Duration (sec)	Heat Load (J/cm2)
8'HTT	155	2	6	90	540
		3	11	90	990
		6	16	90	1440
		9.1	20	90	1800
LHMEL	103	NA	16	90	1440
		NA	20	90	1800
		NA	30	90	2700
		NA	37.5	120	4500
PTF	103	0.95	16	70	1120
		1.4	24	70	1680
		1.7	30	70	2100

IRVE-3 TPS Ground Testing

EDL-SA

Facility	Sample Size (cm2)	Surface Pressure (kPa)	Heat Flux (W/cm2)	Duration (sec)	Heat Load (J/cm2)
8'HTT	155	2	6	90	540
		3	11	90	990
		6	16	90	1440
		9.1	20	90	1800
LHMEL	103	NA	16	90	1440
		NA	20	90	1800
		NA	30	90	2700
		NA	37.5	120	4500
PTF	103	0.95	16	70	1120
		1.4	24	70	1680
		1.7	30	70	2100



Contact Conductance

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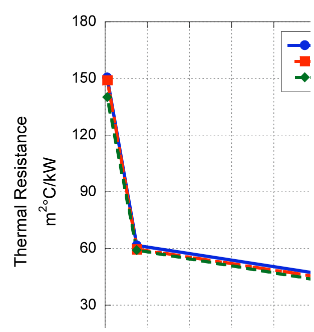
- **IRVE lab test data indicated that contact conductance sensitive to ambient pressure**
- **IRVE layup similar to PAIDAE tested materials**



Calculated Sled Heat Flux

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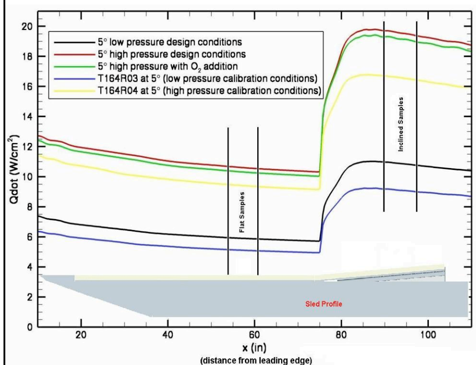

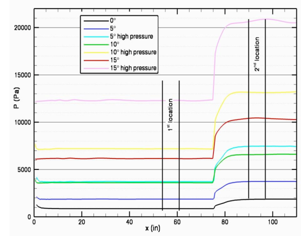

- **VULCAN**
  - **3D CFD chemically frozen code**
  - **Calculations validated by surface pressures**
- Geometry
  - 0.020" full radius leading edge
  - ~75" flat plate
  - 36" after 5° compression

Initial Thermal Assumptions

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Condition	Sample AoA (deg)	Sled AoA (deg)	Location 1 (Flat)		
			Heat Flux (W/cm²)	Pressure (Pa)	Material Contact Conductance (W/m²-K)
B	5	5	5.9	1860	13.7
C, high P	5	5	11.0	3720	16.9

Condition	Sample AoA (deg)	Sled AoA (deg)	Location 2 (Ramp)		
			Heat Flux (W/cm²)	Pressure (Pa)	Material Contact Conductance (W/m²-K)
B	10	5	11.0	3740	16.9
C, high P	10	5	20.0	7460	18.2

Contact Conductance based on lab test data for the IRVE layup

Current Sled cont.

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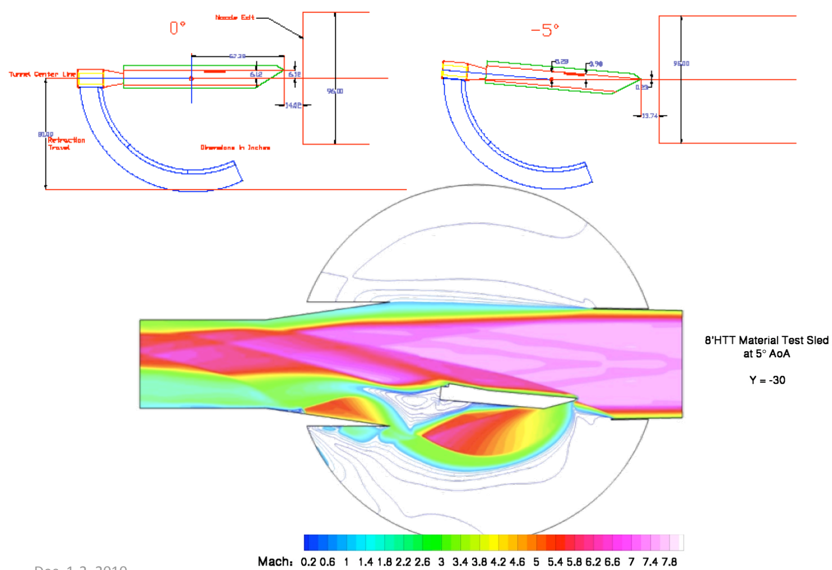

IRVE-3 Trajectory Heating

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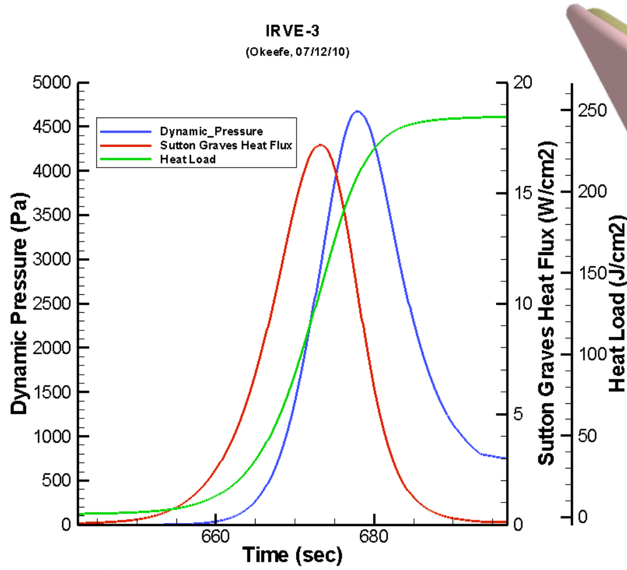
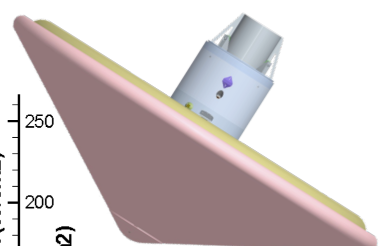
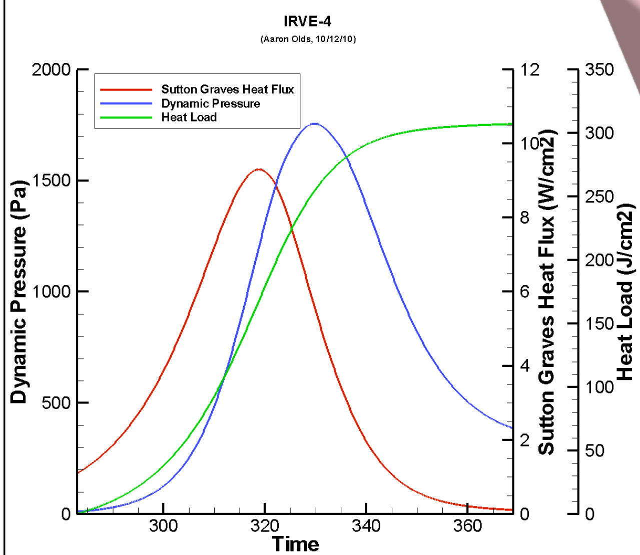
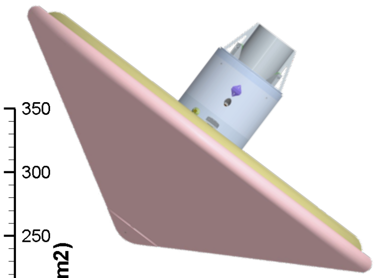




EDL-SA

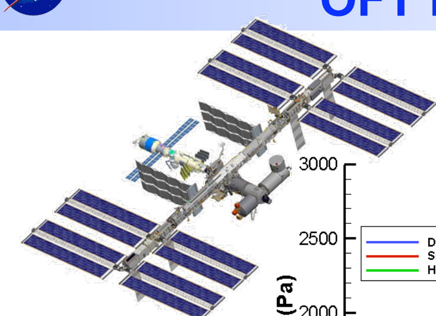
IRVE-4 Trajectory

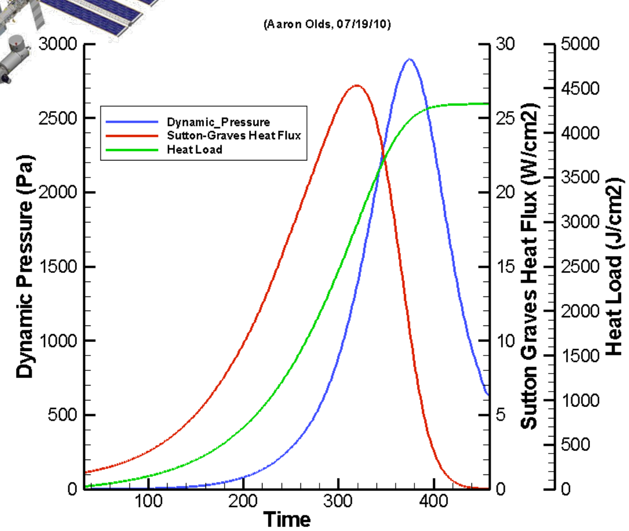




EDL-SA

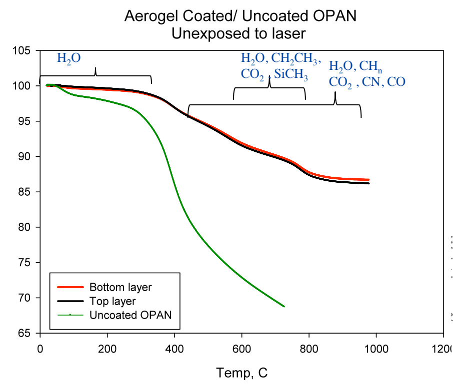
OFT Heating

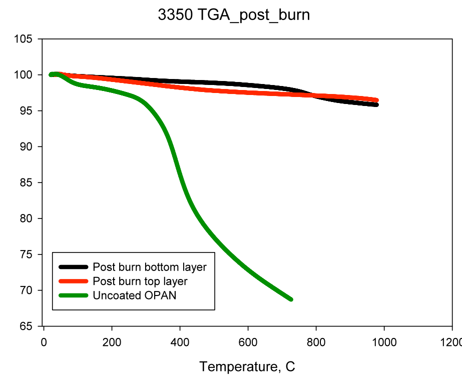




TGA- Post LHMEL test 3350

EDL-SA



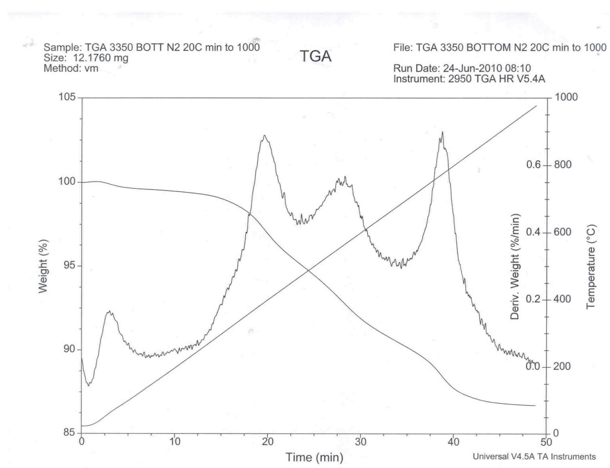


•Sample taken from outer edge of post burn Pyrogel 3350 (not exposed directly to laser)
•Aerogel coated OPAN experiences less wt loss at higher temp than virgin OPAN
•Releases water, carbon dioxide, nitriles and various hydrocarbons during heating

•Sample taken from center burn source of post burn 3350
•Post burn layers show minimal further thermal degradation
•Release of water and hydrocarbons

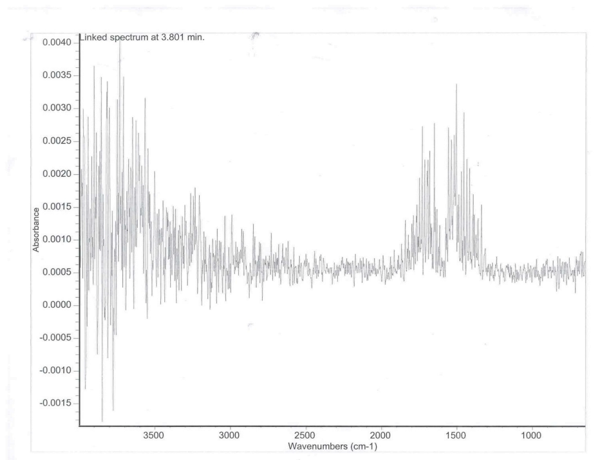
TGA

EDL-SA



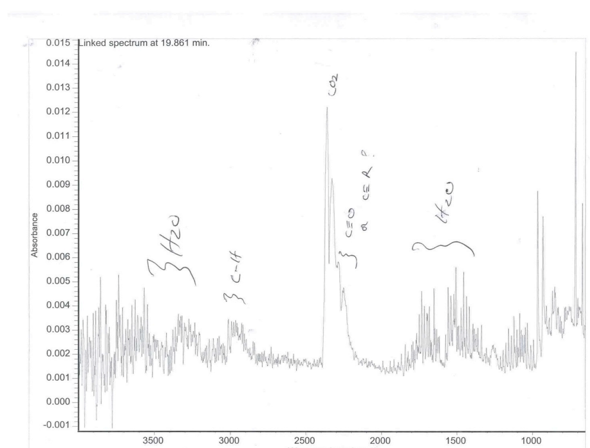
FTIR (~75°C)

EDL-SA



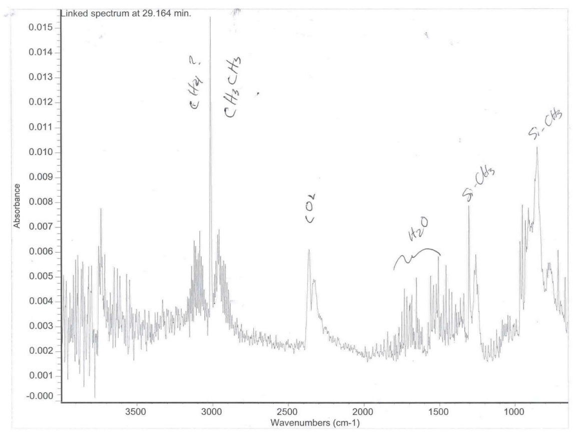
FTIR (~375°C)

EDL-SA



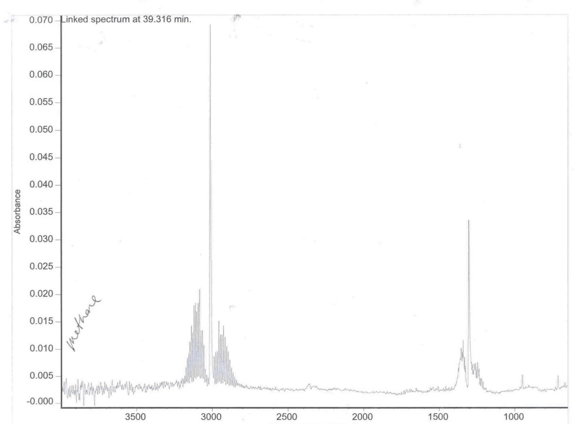
FTIR (~575°C)

EDL-SA



FTIR (~775°C)

EDL-SA

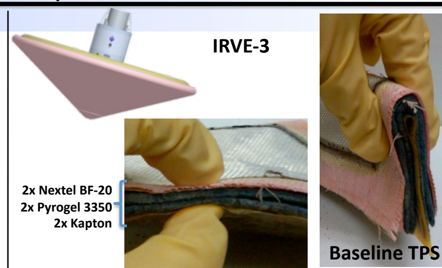


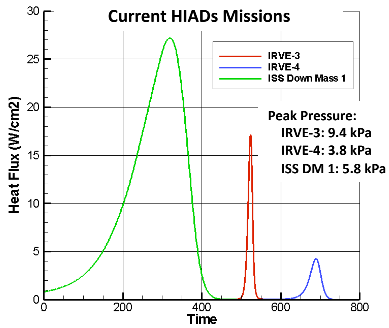
Flexible TPS
(Del Corso)

EDL-SA

Mission Relevance

<u>Enabling</u> for Human Earth and Mars Hypersonic Inflatable Aerodynamic Decelerators (HIADs). Specifically, flexible insulating TPS is an enabling technology for EDL-SA Architectures when heating rates are less than 50 W/cm^2 for long duration entry profiles, or even higher heating rates for shorter duration entry trajectories. This technology is also enabling for the proposed IRVE-3, IRVE-4, ISS Down Mass, and Mars missions.





Flexible TPS: Current TRL is 4

- **Extensive ground tests performed at relevant HIAD flight conditions verifying survivability**
- **TPS survives near-zero bend radius without degradation to mechanical properties, or particulation (mass loss)**
- **Thermal Desktop thermal response model verified against ground tests**

Potential maturation timeline:
One insulator to TRL 6 by FY12 under HIADs. Multiple insulators at TRL 6 by FY14 supporting ISS Down Mass , and Mars missions.

EDL-SA

7.0 HIAD Controllability Assessment Objectives and Overview

Dick Powell

EDL-SA

Objective

- Background
  - EDL-SA Year 1 considered only bank control and HYPAS guidance
  - Bank angle control typically requires 5 deg/s^2 acceleration and 20 deg/s max rate – concern that this requirement could induce undesirable dynamics
- EDL-SA Year 2 Objective
  - Examine alternative HIAD control methods. Determine if at least one credible control strategy existed for HIADs
  - Direct cg control selected as alternate control concept (note: felt that there was insufficient time to consider shape control)
  - Other potential controllers identified – not examined due to time limitations

Strategy

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- Controllability assessment performed on Aerocapture only
  - Simpler than EDL
    - Only hypersonic flight – aerodynamics ~constant for entire phase
    - No transitions (violated when we added guidance-directed jettisoning)
    - Targeting is simpler
    - Control algorithm development easier
- Add EDL if time permitted

Desired Controllability Assessment

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Completed
Partially complete
Not started

- Trades
  - L/D (0.1, 0.25)
  - Approach Velocity (7.3 km/s, 5.8 km/s)
  - Final Orbit (500km Circular, 1 sol)
  - Control trades (Bank Angle, cg1, cg2, cg3…)
  - HIAD used through entire atmospheric pass vs. Guidance control of HIAD Jettison
- No known guidance algorithm tested over all these conditions or utilizes cg control
- Employed 4 guidance algorithms
  - Did not want a particular guidance characteristic to influence the answer
  - Maximize likelihood that that a solution to each of the cases would be found
  - 3 evaluated in 2005 CNES-led MSR Orbiter evaluation (HYPAS, TPC, NPC)
  - 1 new (Shape Integral)
  - Objective was to fully understand the guidance/control interaction
- Study incomplete and inconclusive

7.1 EFF Controllers

Eric M. Queen

Overview

- Bank Angle Controller
  - Description
  - Results
  - Preliminary Thruster sizing
- CG controller
  - Description
  - Results
  - Issues with CG control
- Conclusions

Bank Angle Controller

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- CG fixed
- Bank command taken from guidance
- Combination of roll and yaw torques used to rotate vehicle about velocity vector
- Pitch channel primarily provides rate damping
- Gains derived using LQR methodology
  - Developed to limit rates, accelerations
  - Indexed on relative velocity
- Pure torques in roll, pitch, yaw assumed available
- Aerocapture and Entry use same formulation with different gains

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Linear Quadratic Regulator (LQR) Approach

- “Linear-Based” controller based on NASA LaRC proposed MSP ’01 Lander controller and proposed MSL controller
- Similar to system flown for lateral/directional control of Pegasus
- Provides a systematic approach to multi-input / multi-output (MIMO) control design
- Multi-variable control design methodology
  - Uses equations of motion linearized along entry trajectory
  - Feedback gains selected by minimizing a “quadratic” performance index (cost function)
  - “Quadratic” means cost function is weighted sum of squares of state errors and control effort
  - Linear control equation

$$u = Kx$$

  - Continuous control commands

LQR Controller Structure

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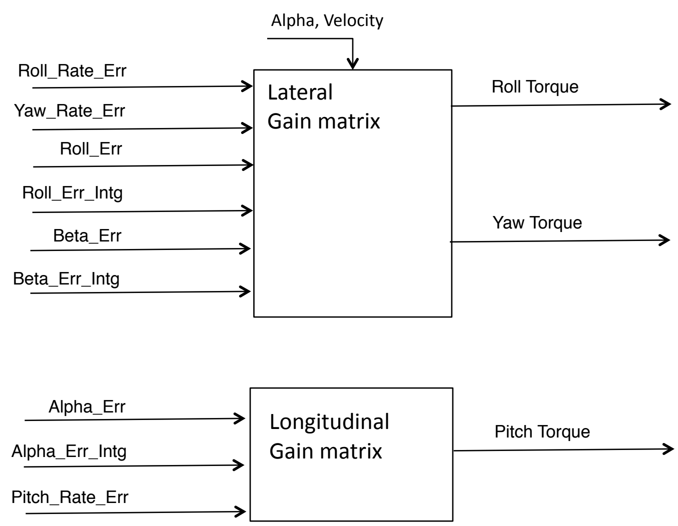
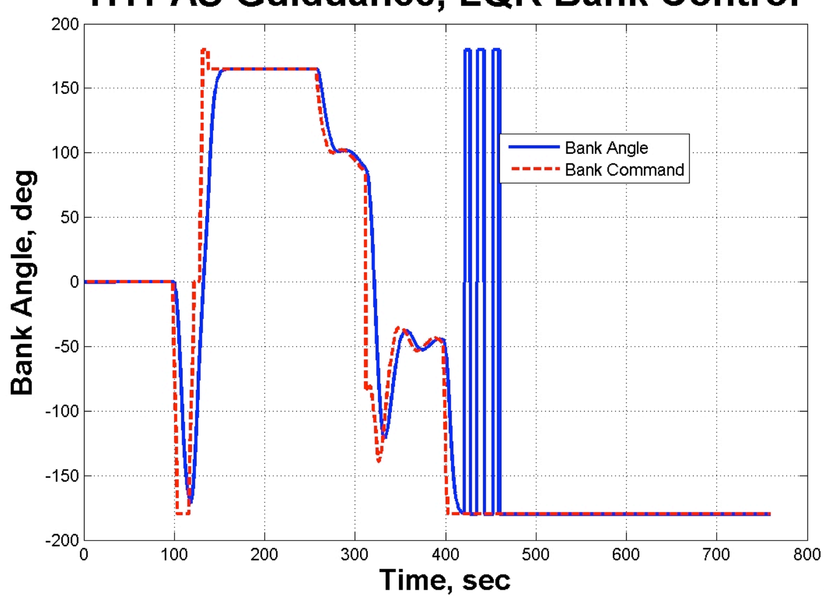


EDL-SA

HYPAS Guiduance, LQR Bank Control



emq - 1

Apollo Entry Guidance

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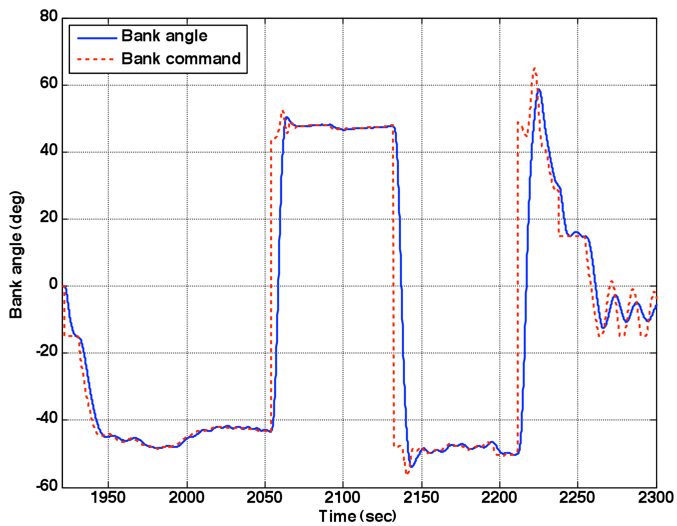
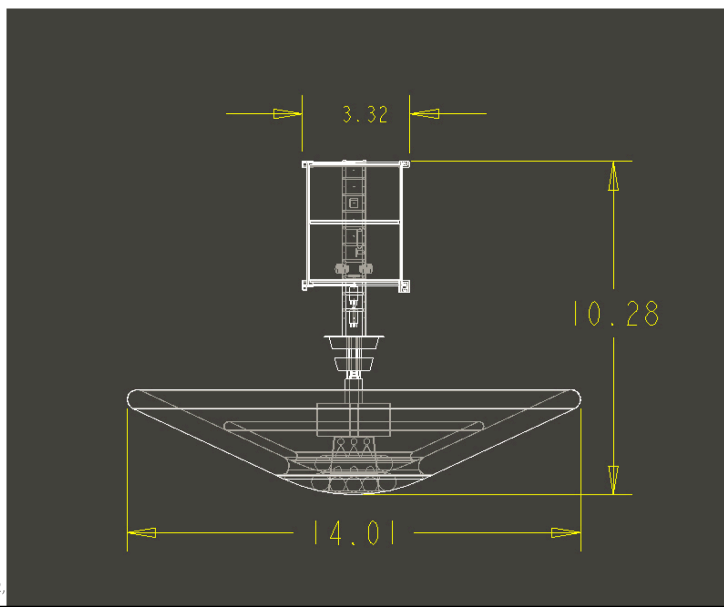


Vehicle Configuration for Thruster Sizing

EDL-SA



Assumed Thruster Arrangement

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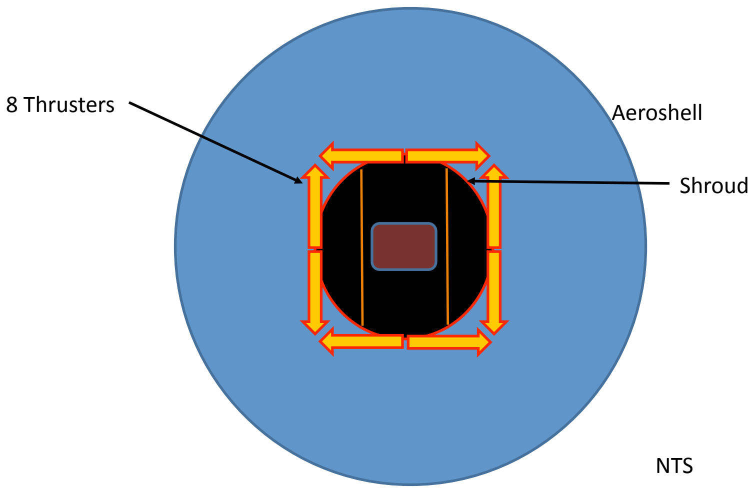


Sizing RCS thrusters for Bank Control

EDL-SA

- **Assumptions:**
  - **Bank acceleration: 5 deg/s^2**
  - **Angle of Attack: 20 deg**
  - **8 thrusters arranged in cross formation**
  - **Thrusters attached to minimal cylindrical shroud covering payload**
  - **Moments of inertia scaled up from payload MOI by mass**
  - **CG of descent engines/HIAD 1m forward of interface plane**
  - **6969 kg total mass**

Thruster Sizing

EDL-SA

- Thrust_yaw = Izz*bank_accel*cos(alpha)/(2*L_z)
  = 61 N
- Thrust_roll = Ixx*bank_accel*sin(alpha)/(4*L_x)
  = 23 N
- Thruster size = max(Thrust_yaw, Thrust_roll)
  = 60.7 N
  = 13.7 lbf

- Must add margin for:
  - Non-tangential pointing
  - Impingement losses
  - Mass/MOI growth

CG Control Strategy

EDL-SA

- "CG controller" is really a combination of CG control and RCS control
  - Roll channel is commanded to maintain constant roll angle of 0
    - PID control based on roll angle, roll rate
    - Pure roll torque is applied to vehicle
  - Pitch, yaw channels are controlled via motion of vehicle payload relative to aeroshell
    - PID in each axis based on vertical, horizontal L/D and pitch and yaw rates
    - Payload mass is moved

Entry CG Control Overview

EDL-SA

- Entry CG control is implemented such that Zcg provides direct alpha control and Ycg provides direct beta, or sideslip, control (Ycg = gain * crossrange error)
  - Each CG channel is controlled separately and independently
  - Xcg will dictate the amount of Zcg required to provide necessary L/D (as Xcg goes toward neutral static stability, the required Zcg range is reduced)

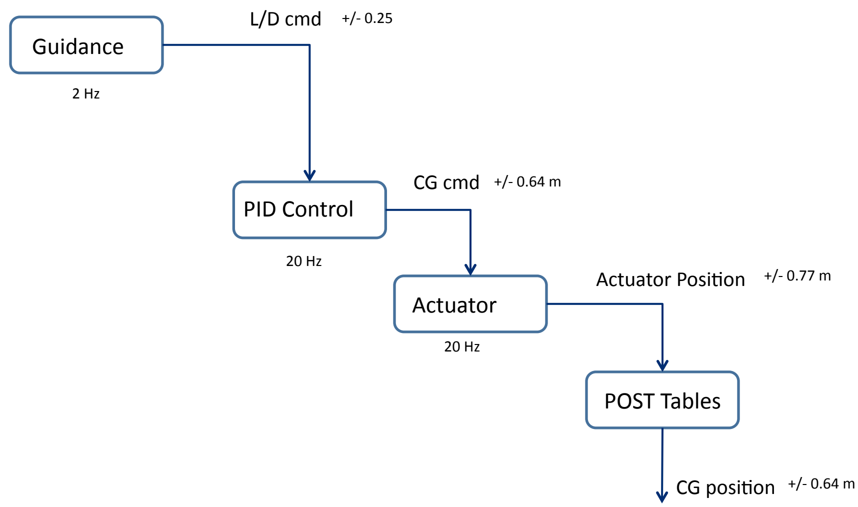
CG Controller

EDL-SA

- Roll gains chosen to maintain 0 roll angle in nominal aerocapture pass
  - Roll torque limited to 5 N*m
- Y,Z CG gains chosen to perform doublet maneuver +/- 0.2 L/D
  - Rates limited to 0.2 m/s (~8"/s)
- Currently, integral gains are small or zero
- Tested/Tuned on TPC aerocapture guidance
- At low dynamic pressure (<2 Pa ~ 0.01 g's) aerodynamic torques are inadequate to trim vehicle. CG control becomes infeasible.
  - Rate limits squashed at low dynamic pressure to limit CG motion.
  - Low dynamic pressure rates limited to 0.0127 m/s (~0.5"/s)
  - Moved X CG forward to 0.30 X/D to increase stability

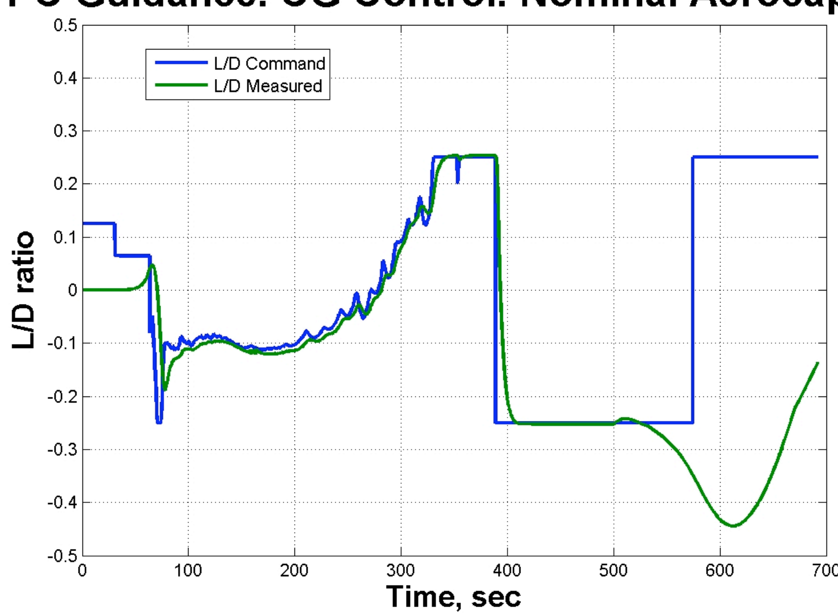
CG Control in POST

EDL-SA



EDL-SA

TPC Guidance. CG Control. Nominal Aerocapture



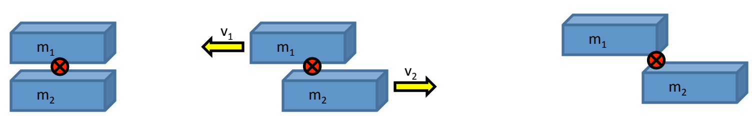
CG Control Issue

EDL-SA

- **CG control is performed by moving massive components relative to aeroshell**
- **Several possible mechanisms to allow mass motion**
  - **Assumed payload mass moves on some type of rail system**
  - **Translation relative to aeroshell without rotation**
- **Mass motion changes moments of inertia of total vehicle**
- **Violates assumption of rigid body**
- **Imparts unmodeled moment on aeroshell**

Angular momentum of linearly translating masses

EDL-SA



h = 0 $h \neq 0$ h = 0

$h = m_1 * r_1 * v_1 + m_2 * r_2 * v_2$

$dh/dt = m_1 * r_1 * a_1 + m_2 * r_2 * a_2$

This effect is currently not fully modeled in POST.
Violates rigid-body assumption.

r1, r2 are distances from mass 1, 2 centers to common center of mass

In general, for several masses,
$dh/dt = \Sigma\, m_i * r_i * a_i$
where the r_i are the distances to the common center of mass, and allowance is made for the signs of the r's and a's.

Conclusions

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- **Working controllers in place for:**
  - Bank modulated Aerocapture
  - CG modulated Aerocapture
  - Bank modulated Entry
- **RCS (or other) angular controller is always required even with CG control.**
- **Future Work:**
  - Need to develop RCS control system for low dynamic pressure flight regimes
  - Model individual thrusters, positions and pointing
  - Model system lags, discretization
  - Need to investigate use of RCS for damping; concurrent w/ CG for trim
  - Model dynamics of internal mass motion
  - Model flexure between aeroshell and hard center body

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Backup

Bank Angle Controller Design Process

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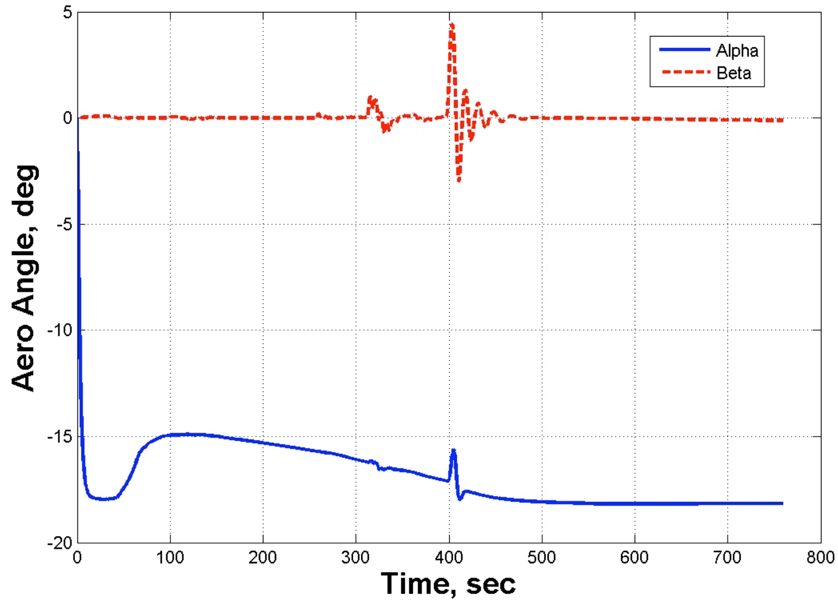
- Inputs:
  - 3Dof reference trajectory (preferably in-plane lift only)
  - 6Dof Aerodynamics
  - Vehicle moments of inertia

Bank Angle Controller Design (2)

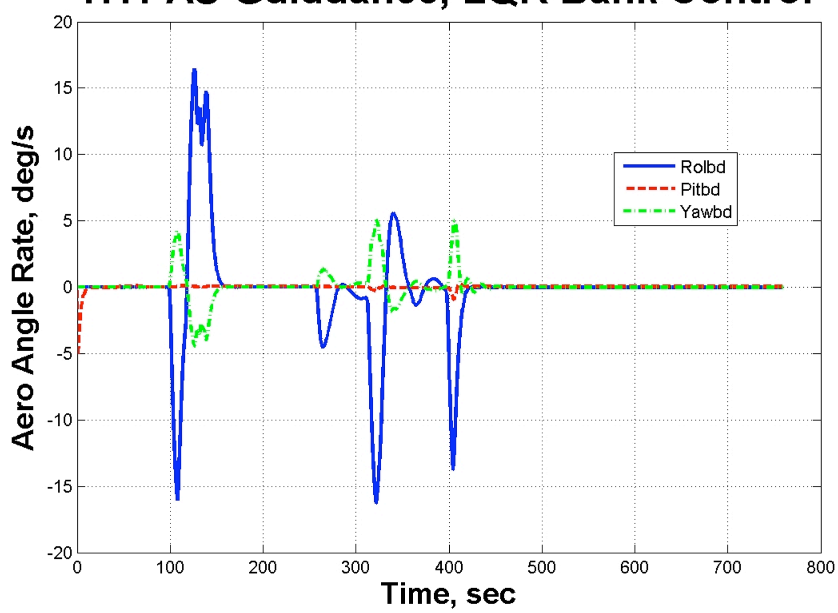
EDL-SA

- Pick design points along reference trajectory
- Linearize system model at chosen design points
- Choose weights to use in solution of matrix Riccatti equation
- Solve Riccatti equation for gain matrices
- Check performance in linear, frozen-state simulation
- Check performance in 6dof POST2 simulation

HYPAS Guiduance, LQR Bank Control



HYPAS Guiduance, LQR Bank Control



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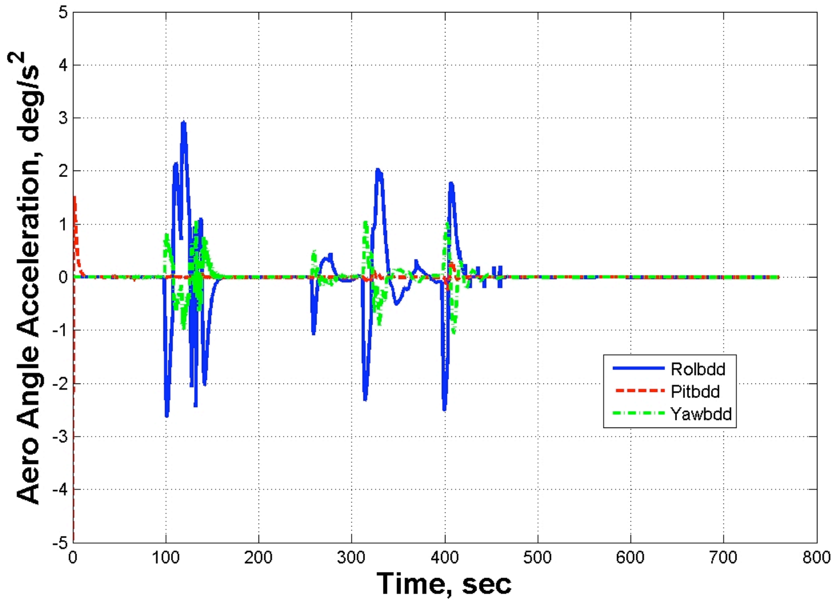
HYPAS Guiduance, LQR Bank Control



emq - 3

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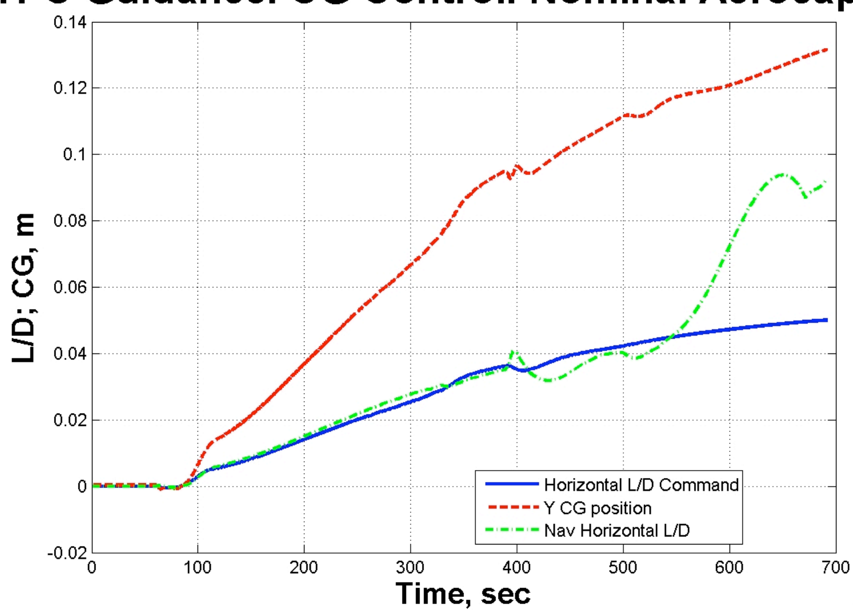
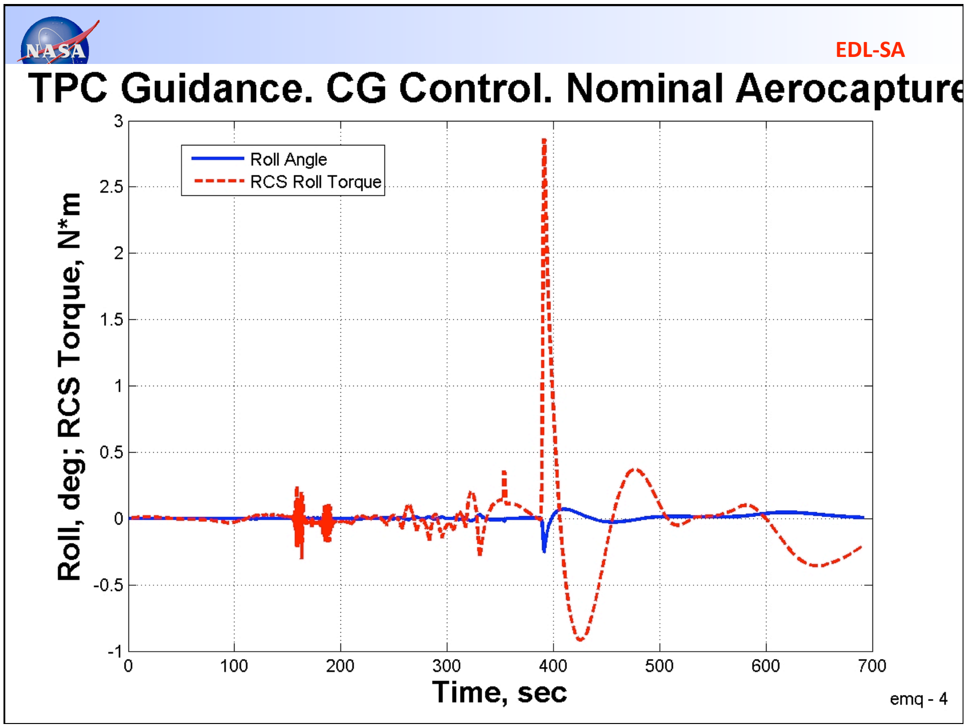
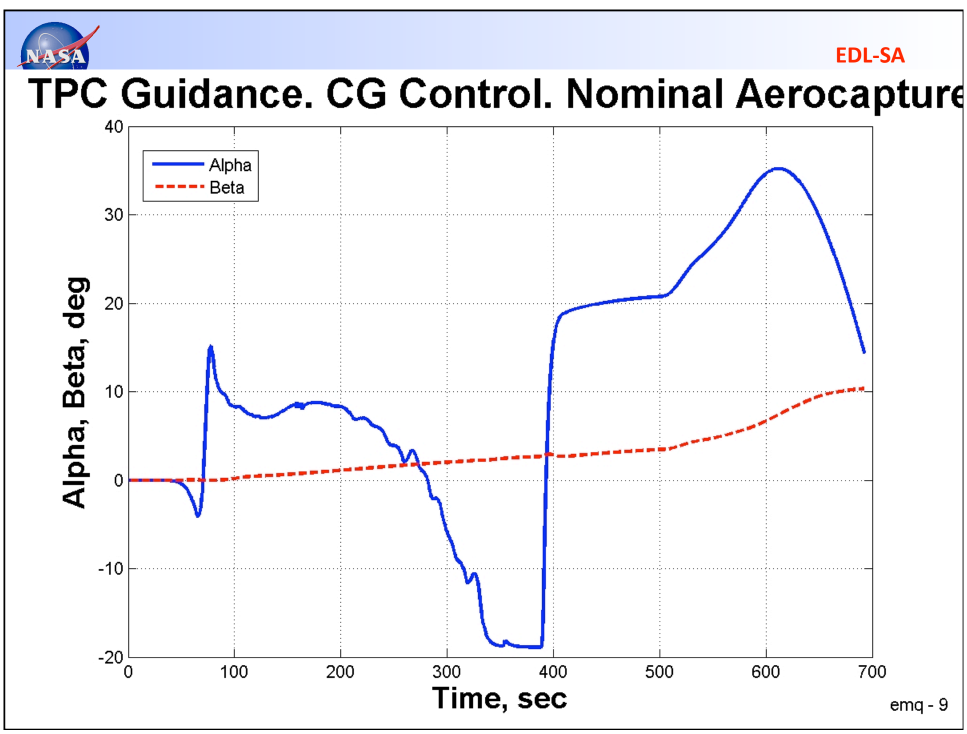
TPC Guidance. CG Control. Nominal Aerocapture



emq - 5

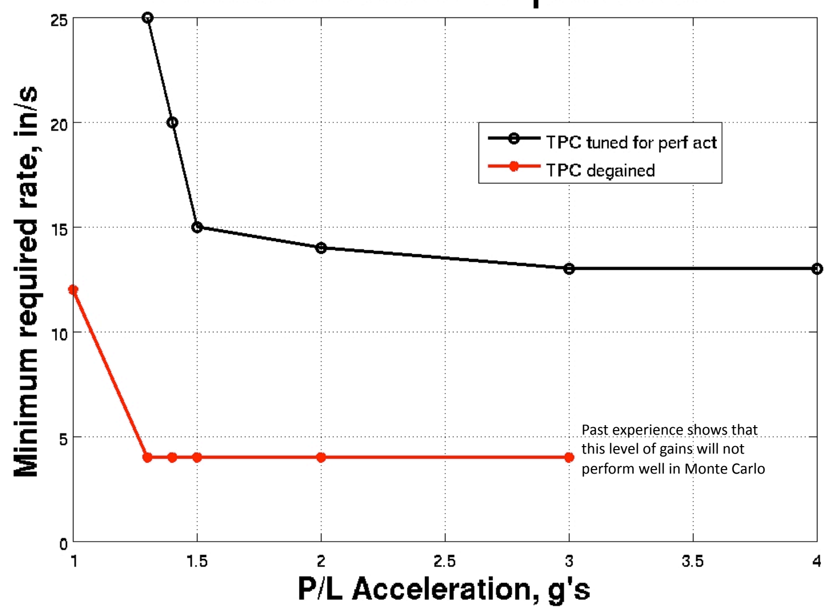


EDL-SA
TPC Guidance. CG Control. Nominal Aerocapture
Roll Angle
RCS Roll Torque
Roll, deg; RCS Torque, N*m
Time, sec
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
100
200
300
400
500
600
700
emq - 4

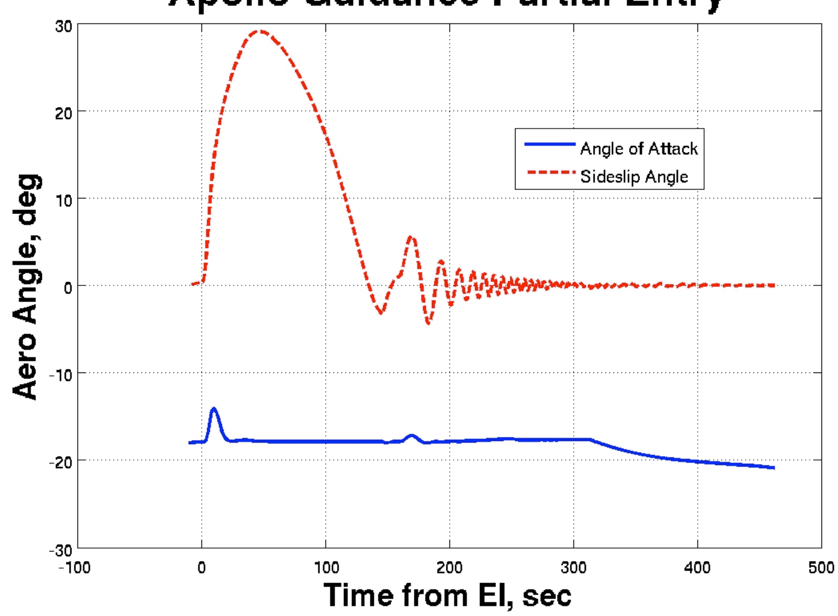


EDL-SA
TPC Guidance. CG Control. Nominal Aerocapture
Alpha
Beta
Alpha, Beta, deg
Time, sec
40
30
20
10
0
-10
-20
0
100
200
300
400
500
600
700
emq - 9

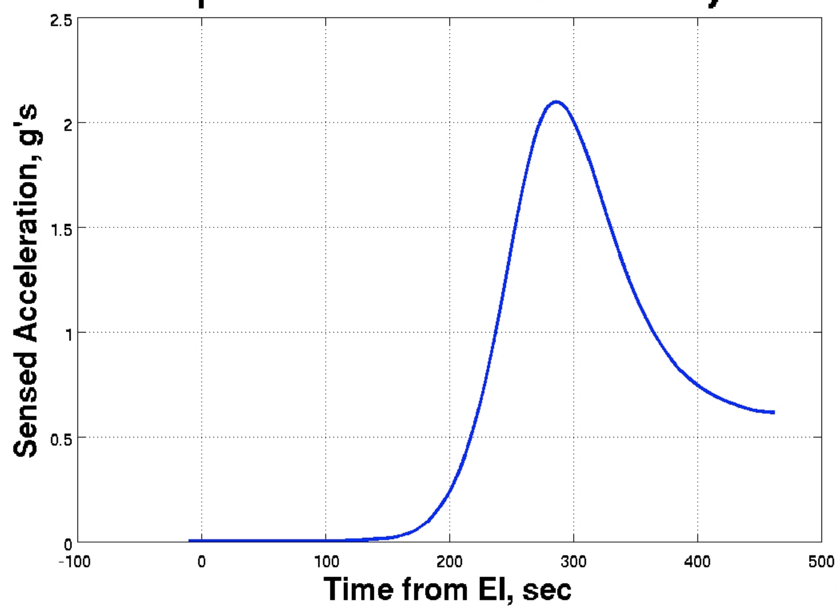
Pseudo-actuator requirements



Apollo Guidance Partial Entry

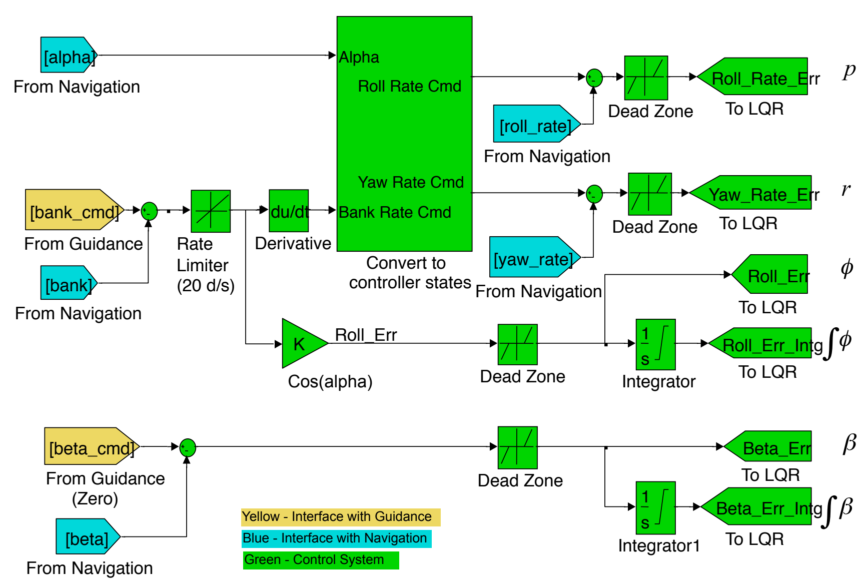


Apollo Guidance Partial Entry



Lateral / Directional State Error Computation

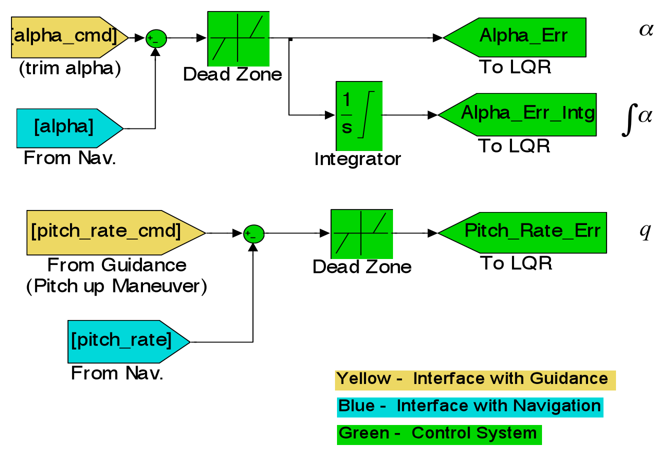
(Convert guidance commands to controller feedback error states)



Longitudinal State Error Computation

EDL-SA

(Convert guidance commands to controller feedback error states)



PID CG Controller

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- Three independent axes. Guidance commands:
  – Roll (=0)
  – Z CG
  – Y CG
- Proportional-Integral-Derivative control of each axis
- Input variables:
  – Roll angle, integral of Roll angle , Roll rate
  – Vertical L/D, integral of Vert L/D, Alpha dot
  – Horizontal L/D, integral of Horz L/D, Yaw rate

  Mix-matched
- Control variables:
  – Roll torque
  – Vertical CG position
  – Horizontal CG position

EDL-SA

7.2 Aerocapture Performance and Trade Study

Carlie Zumwalt
Richard Powell
Eric Queen
David Way

Aerocapture and Performance and Trade Study Overview

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- **The primary objective is to show aerocapture performance for the EFF configuration**
- **Three Trades were completed for the aerocapture performance study**
  - 8000 case Monte Carlos were run for each segment of the trade study

Trade 1: Variation in L/D (0.25 vs 0.10)

- Current IAD designs are showing difficulty obtaining an L/D of 0.25, therefore can the current EFF vehicle configuration successfully aerocapture with less lift to command?
  → Evaluated by TPC, HYPAS, NPC, and Shape Integral Guidances

Trade 2: Jettison vs No Jettison of HIAD during aerocapture

- If we incorporate the Jettison maneuver as an added control parameter, do we increase the vehicle's ability to hit the target apoapsis for an L/D of 0.1?
  → Evaluated by TPC, HYPAS, NPC, and Shape Integral Guidances

Trade 3: Variation in Post-Aerocapture Target Orbit

- How does the performance change when the target orbit apoapsis is adjusted from 500km circular to a more difficult 1 sol orbit (33,793km x 250km)?
  → Evaluated by HYPAS Guidance

Aerocapture Overview

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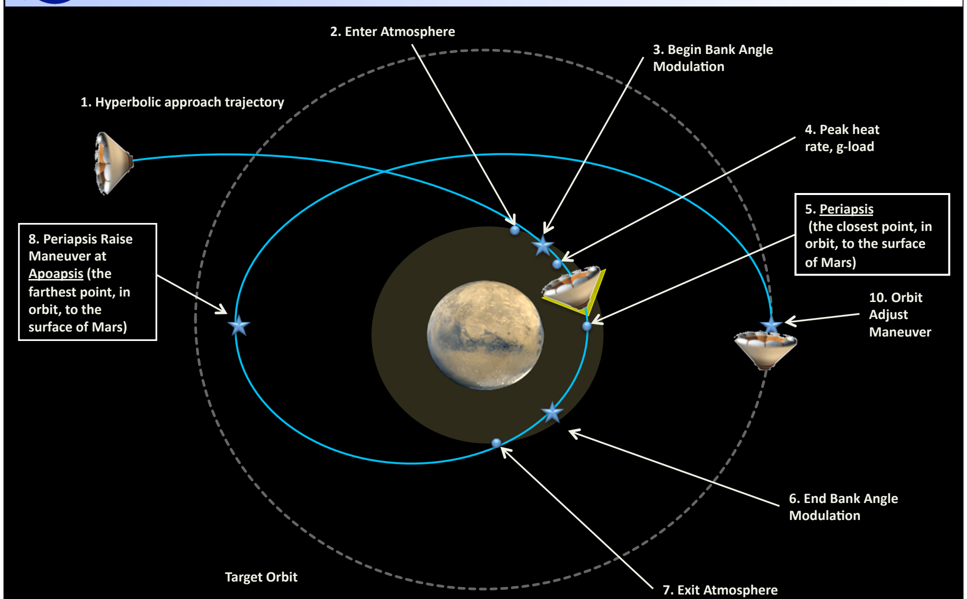

Nominal Inputs

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Mission Parameters

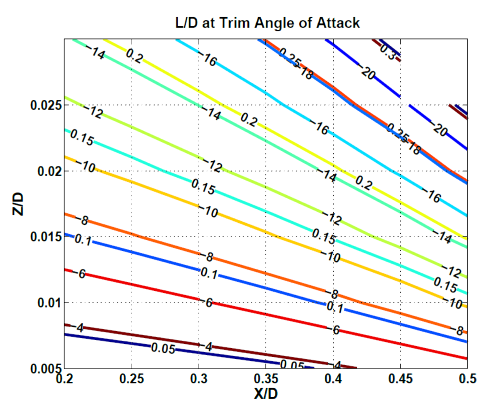
- Aeroshell Diameter = 14 m
  - → Sized to meet 50 W/cm² 3-sigma Peak Heat Rate
- Vehicle Diameter = 4 m
- Ballistic Coefficient = 33 kg/m²
- Lift-to-Drag Ratio = 0.25
  - X/D = 0.30
  - → Corresponds to an alpha of -18.2 degrees
- 3-burn ΔV Calculation
  - $\Delta V_{TOT} = \Delta V_{PRM} + \Delta V_{PCM} + \Delta V_{AR/LM}$
  - 2-burn budget ($\Delta V_{AR/LM} + \Delta V_{PRM}$) = 150 m/s
  - ΔV_{PCM} budget = 100 m/s
- Target Orbit : 500km circular
- Bank Control
  - Bank Rate : 20 deg/s
  - Bank Acceleration : 5 deg/s²

Nominal Initial State

- Entry Flight Path Angle : Guidance Dependent
- Hyperbolic Excess Velocity = 5463.59 m/s
  - Relative Entry Velocity = 7360.23 m/s
  - Relative Entry Azimuth = 359.99 deg
  - Radius at Entry Interface = 3522.250 km
- V_∞ Right Ascension = 90 deg
- V_∞ Declination = 2.99 deg
- B-plane Angle = 270 deg
- Julian Date = 2456862.0

SIM Details

- Mars-GRAM Atmosphere
- 65deg Sphere Cone AeroDatabase
- Simple Nav Propagator
- Dave Kinney's Aeroheating Indicators
- Target angular momentum vector (normalized)
  - {-1.0,0.0,0.0}



Monte Carlo Dispersions

EDL-SA

Parameter	Nominal Value	Dispersion	Units	Distribution
Initial State				
Entry Flight Path Angle	Guidance Dependent	+/- 0.25	deg	Normal
Hyperbolic Velocity	5463.59	+/- 20	m/s	Normal
B-plane Angle	270.0	+/- 0.1	deg	Normal
Time of Flight	-30.0	+/- 2.0	sec	Normal
Atmospheric Uncertainties				
Dust Tau	0.45	0.1 to 0.9	[nd]	Uniform
Perturbation Seed Number	1	1 to 29999	[nd]	Integer
Density Multiplier	1.0	+/- 15%	[nd]	Uniform
Initial Attitude and Rate Uncertainties				
Alpha	-7 for L/D 0.10 -18.0 for L/D 0.25	+/- 0.25	deg	Normal
Beta	0.0	+/- 0.25	deg	Normal
Bank Angle	0.0	+/- 0.25	deg	Normal
Roll Rate $_{BODY}$	0.0	+/- 0.10	deg/s	Normal
Pitch Rate $_{BODY}$	0.0	+/- 0.10	deg/s	Normal
Yaw Rate $_{BODY}$	0.0	+/- 0.10	deg/s	Normal
Aerodynamic Uncertainties				
CA Multiplier	1.0	0.9:1.1	[nd]	Normal
CN Multiplier	1.0	0.9:1.1	[nd]	Normal
CY Multiplier	1.0	0.9:1.1	[nd]	Normal
Mass Property Uncertainties				
XCG Bias Location	-0.22486	+/- 0.001	m	Normal
YCG Bias Location	0.0	+/- 0.001	m	Normal
ZCG Bias Location	0.175 for L/D 0.1 0.462 for L/D 0.25	+/- 0.001	m	Normal

Monte Carlo Dispersions

EDL-SA

Parameter	Nominal Value	Dispersion	Units	Distribution
ALHAT IMU Dispersions				
Bias_acc_x	0	+/- 8.250E-04	m/s²	Normal
Bias_acc_y	0	+/- 8.250E-04	m/s²	Normal
Bias_acc_z	0	+/- 8.250E-04	m/s²	Normal
Sf_acc_x	0	+/- 4.050E-04	m/s²	Normal
Sf_acc_y	0	+/- 4.050E-04	m/s²	Normal
Sf_acc_z	0	+/- 4.050E-04	m/s²	Normal
Iseed_acc_x	1	1:29999	[nd]	Integer
Iseed_acc_y	1	1:29999	[nd]	Integer
Iseed_acc_z	1	1:29999	[nd]	Integer
Rnoise_acc	9.05E-05	9.0E-05:9.0E-05	m/s²	Uniform
Bias_gyro_x	0	+/- 1.745E-07	m/s²	Normal
Bias_gyro_y	0	+/- 1.745E-07	m/s²	Normal
Bias_gyro_z	0	+/- 1.745E-07	m/s²	Normal
Sf_gyro_x	0	+/- 2.700E-05	m/s²	Normal
Sf_gyro_y	0	+/- 2.700E-05	m/s²	Normal
Sf_gyro_z	0	+/- 2.700E-05	m/s²	Normal
Iseed_gyro_x	1	1:29999	[nd]	Integer
Iseed_gyro_y	1	1:29999	[nd]	Integer
Iseed_gyro_z	1	1:29999	[nd]	Integer
Rnoise_gyro	1.309E-07	1.309E-07:1.309E-07	m/s²	Uniform

Monte Carlo Dispersions

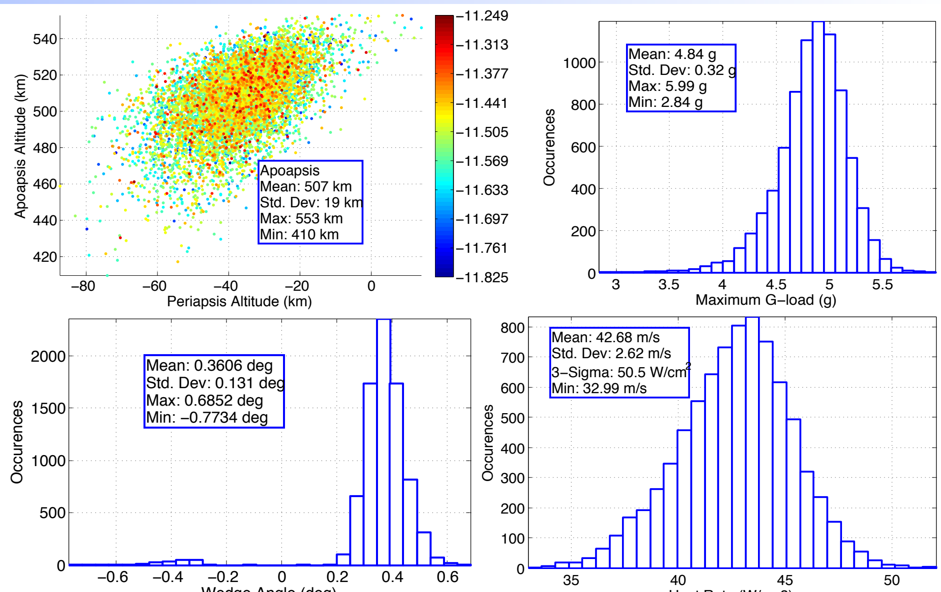
EDL-SA

Parameter	Nominal Value	Dispersion	Units	Distribution
Knowledge Uncertainties				
Ac_xi_delta	0	+/- 2000	m	Normal
Ac_yi_delta	0	+/- 2000	m	Normal
Ac_zi_delta	0	+/- 2000	m	Normal
Ac_vxi_delta	0	+/- 2	m/s	Normal
Ac_vyi_delta	0	+/- 2	m/s	Normal
Ac_vzi_delta	0	+/- 2	m/s	Normal
Ac_ex	0.0	+/- 1.0	[nd]	Normal
Ac_ey	0.0	+/- 1.0	[nd]	Normal
Ac_ez	0.0	+/- 1.0	[nd]	Normal
Ac_att_err_mag	0.0	0.0:1.0	[nd]	Uniform

Monte Carlo Results

Exploration Feed Forward Configuration

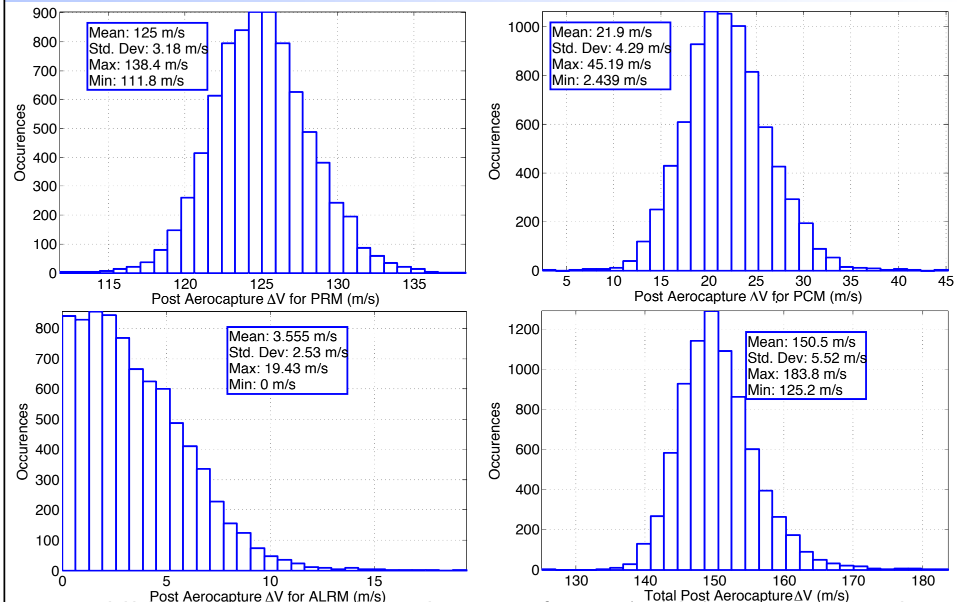
EDL-SA



Monte Carlo Results

Exploration Feed Forward Configuration

EDL-SA



Trade 1 Results

L/D of 0.10 vs L/D of 0.25

EDL-SA

Trade 1: Variation in L/D (0.25 vs 0.10)

- Current IAD designs are showing difficulty obtaining an L/D of 0.25, therefore can the current EFF vehicle configuration successfully aerocapture with less lift to command?

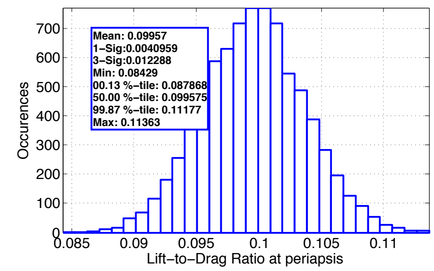
→ Evaluated by TPC, HYPAS, NPC, and Shape Integral Guidances

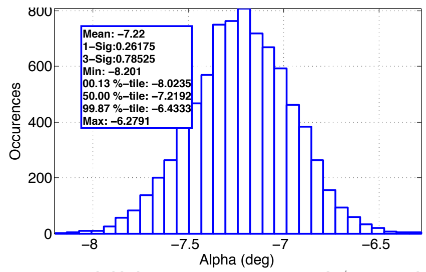
Trade 1 Results

L/D of 0.10 vs L/D of 0.25

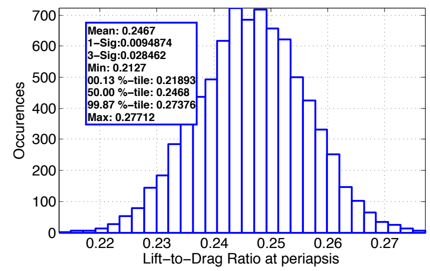
EDL-SA

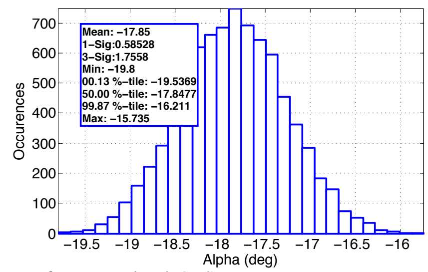
L/D = 0.1





L/D = 0.25



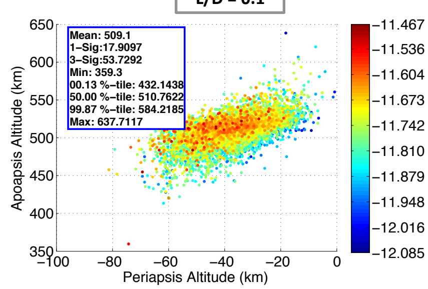


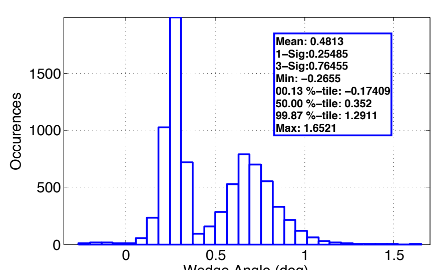
Trade 1 Results

L/D of 0.10 vs L/D of 0.25

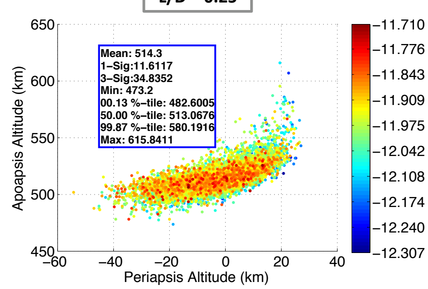
EDL-SA

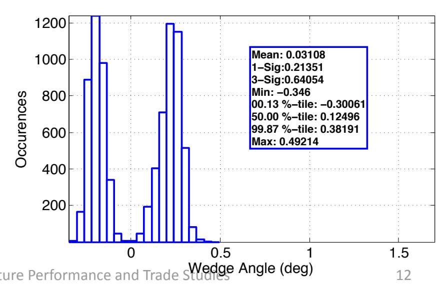
L/D = 0.1





L/D = 0.25



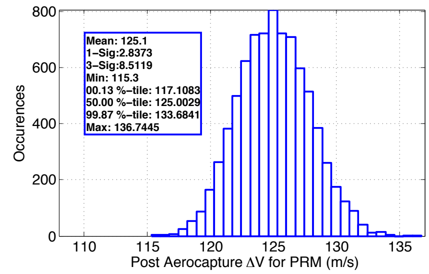


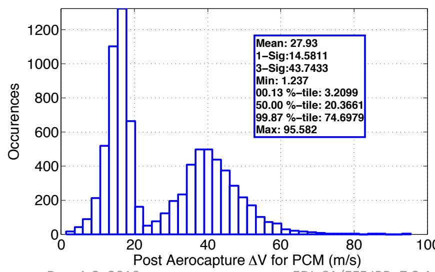
Trade 1 Results

L/D of 0.10 vs L/D of 0.25

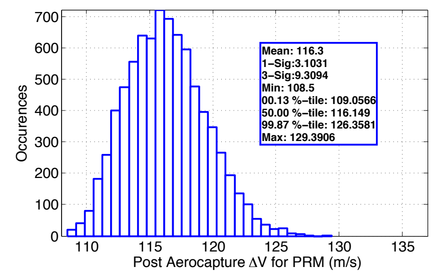
EDL-SA

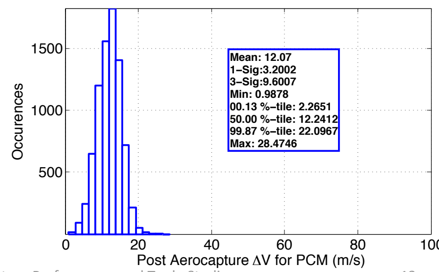
L/D = 0.1





L/D = 0.25



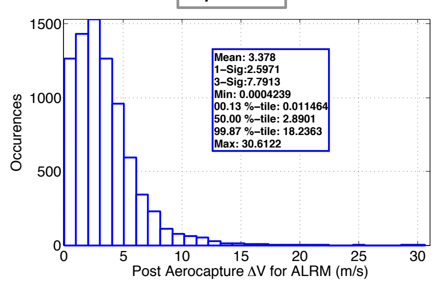


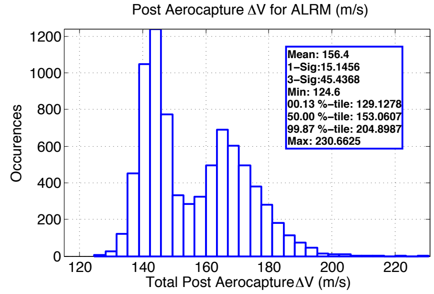
Trade 1 Results

L/D of 0.10 vs L/D of 0.25

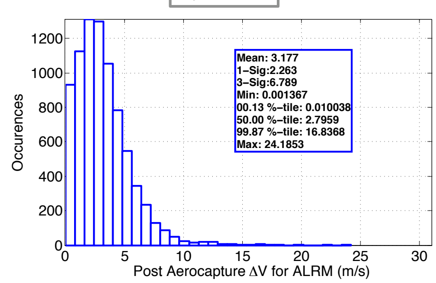
EDL-SA

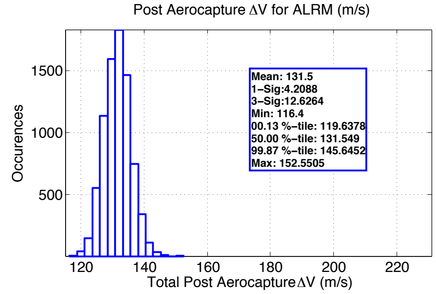
L/D = 0.1





L/D = 0.25





Trade 2 Results

Description of Jettison Event

EDL-SA

Trade 2: Jettison vs No Jettison of HIAD during aerocapture

- If we incorporate the Jettison maneuver as an added control parameter, do we increase the vehicle's ability to hit the target apoapsis for an L/D of 0.1?

  → Evaluated by TPC, HYPAS, NPC, and Shape Integral Guidances

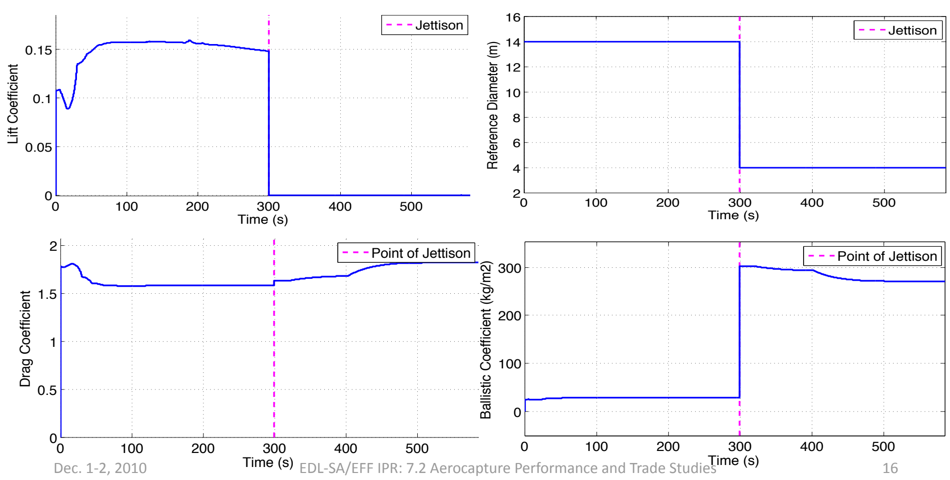
Trade 2 Results

Description of Jettison Event

EDL-SA

The Jettison Event

A calculation made internal to the guidance computes the current value of the orbit apoapsis using nav states. When the current apoapsis value reaches a certain value defined in the guidance, a command is given to shed the HIAD, turn off the guidance, and return alpha, beta and bank angle values to 0 degrees. (NOTE: HIAD separation was not modeled.)



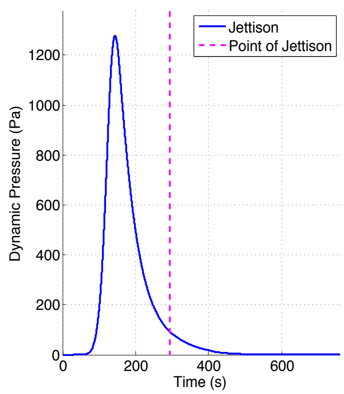
Trade 2 Results

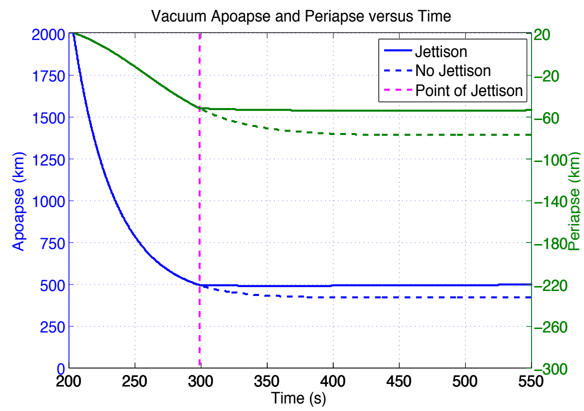
EDL-SA

Description of Jettison Event

The Jettison Event

A calculation made internal to the guidance computes the current value of the orbit apoapsis using nav states. When the current apoapsis value reaches a certain value defined in the guidance, a command is given to shed the HIAD, turn off the guidance, and return alpha, beta and bank angle values to 0 degrees.



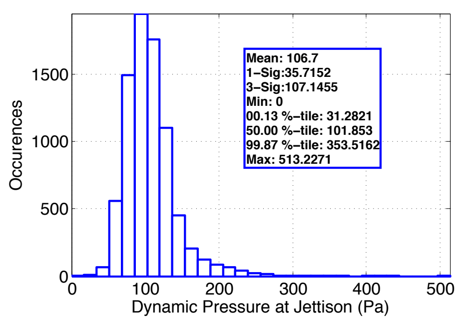


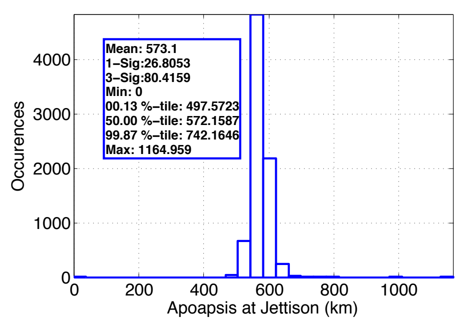
Trade 2 Results

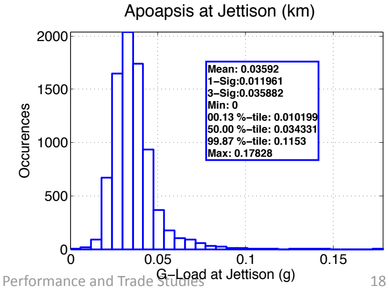
EDL-SA

Jettison Results for L/D of 0.1

Critical Parameters at Jettison Event





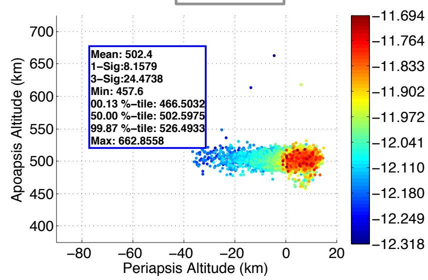


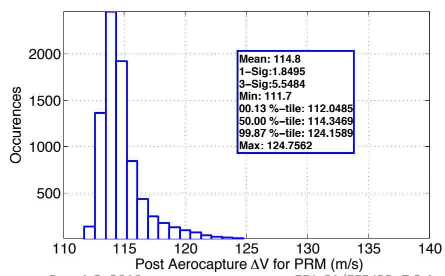
Trade 2 Results

Jettison vs No Jettison Results for an L/D of 0.1

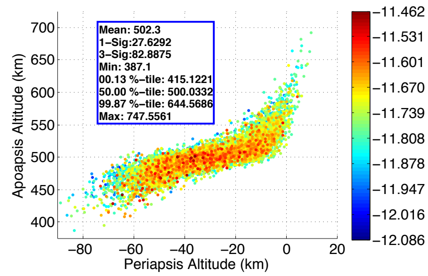
EDL-SA

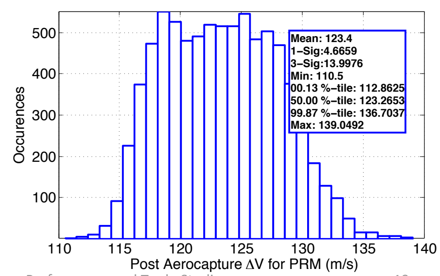
Jettison





No Jettison



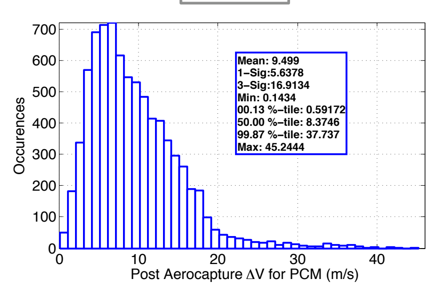


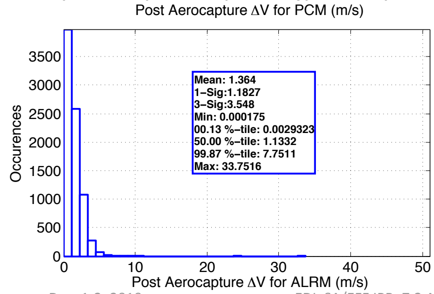
Trade 2 Results

Jettison vs No Jettison Results for an L/D of 0.1

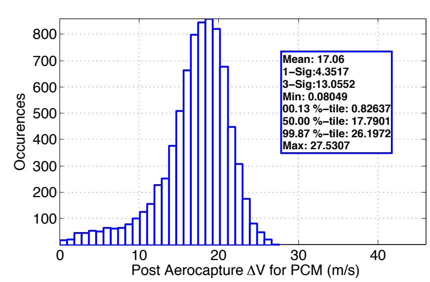
EDL-SA

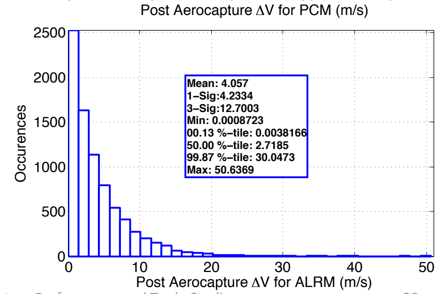
Jettison





No Jettison



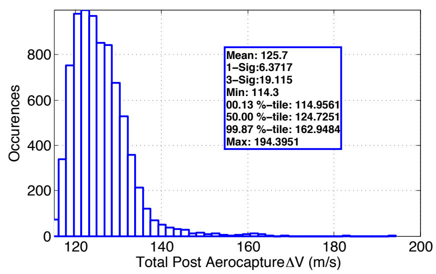


Trade 2 Results

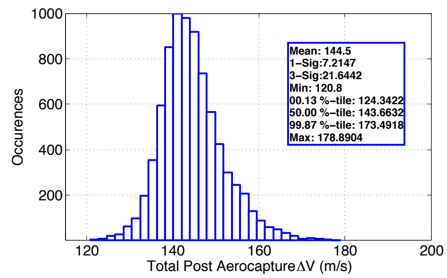
EDL-SA

Jettison vs No Jettison Results for an L/D of 0.1

Jettison



No Jettison



Trade 3 Results

EDL-SA

1 sol vs 500 km circular target orbit for an L/D of 0.25

Trade 3: Variation in Post-Aerocapture Target Orbit

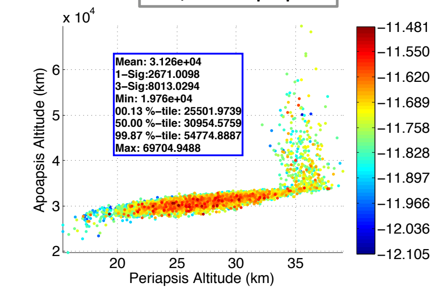
- How does the performance change when the target orbit apoapsis is adjusted from 500km circular to a more difficult 1 sol orbit (33,793km x 250km)?
  - → Evaluated by HYPAS Guidance

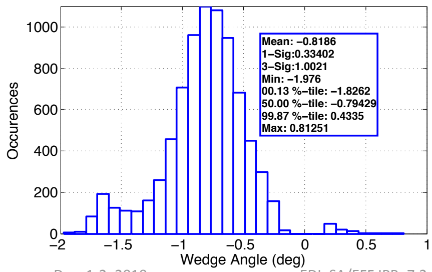
Trade 3 Results

EDL-SA

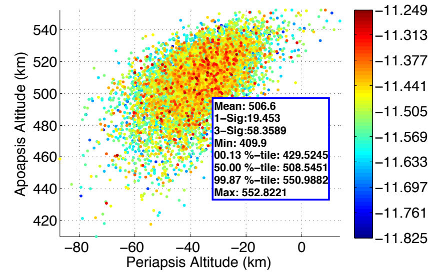
1 sol vs 500 km circular target orbit for an L/D of 0.25

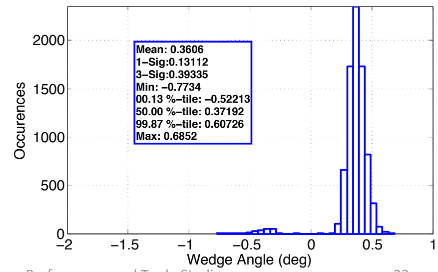
33,793 km apoapsis





500 km apoapsis



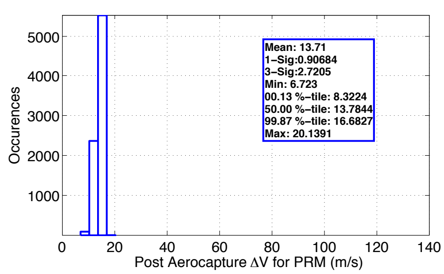


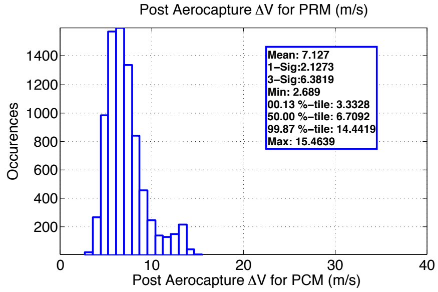
Trade 3 Results

EDL-SA

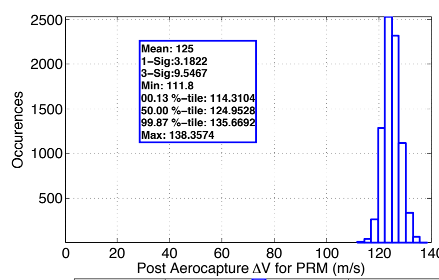
1 sol vs 500 km circular target orbit for an L/D of 0.25

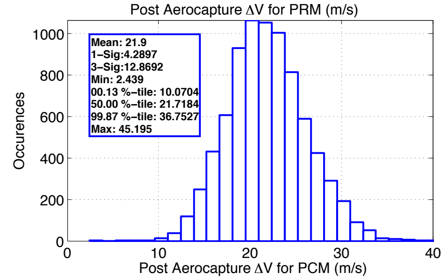
33,793 km apoapsis





500 km apoapsis

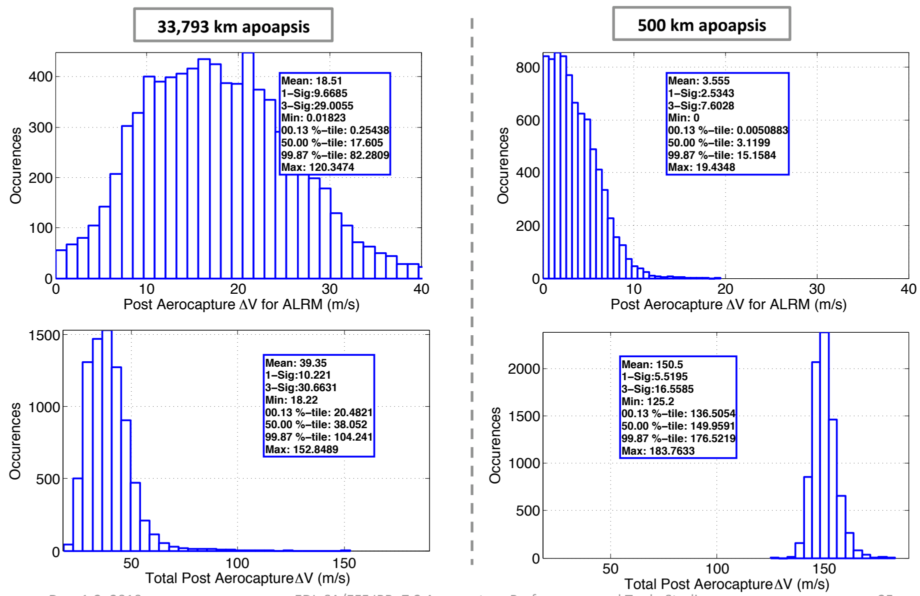




Trade 3 Results

EDL-SA

1 sol vs 500 km circular target orbit for an L/D of 0.25



Summary

EDL-SA

- **Three trades were completed to determine how flying with a lower L/D, jettisoning the HIAD, and targeting a higher apoapsis affects performance.**
  - **Results confirmed that it is much more difficult to fly with less lift available to command, and much more difficult to successfully execute the aerocapture maneuver when the target orbit apoasis is raised, however adding the option to jettison the HIAD atmospherically does aid in allowing the lower L/D cases to reach their target**

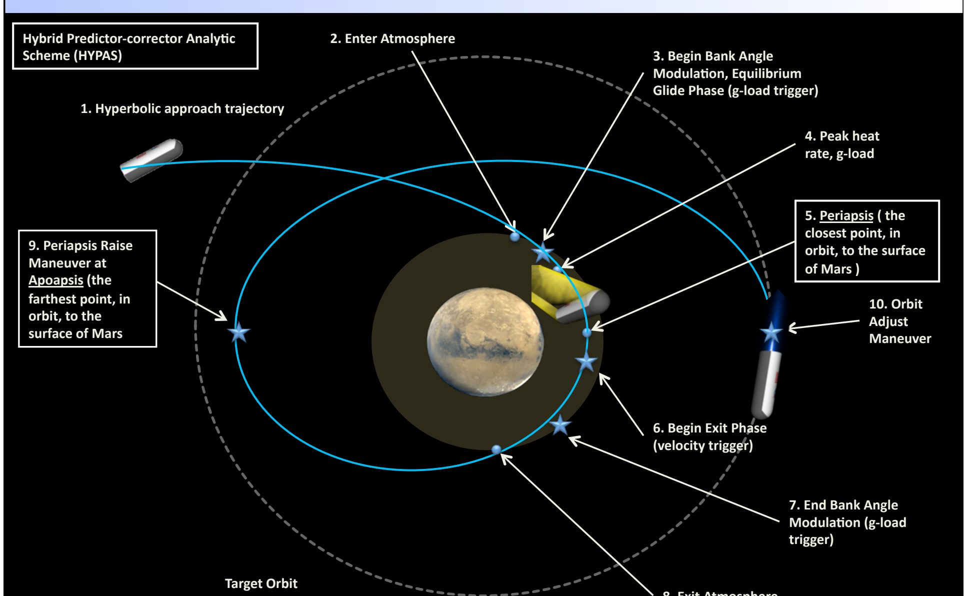
- **For the cases where the HIAD is jettisoned, there are unmodeled effects that would eventually need to be considered (i.e. 6-DOF dynamics, transition, jettison trigger and timing errors, etc)**

- **Each portion of the trade study was successfully executed by the guidance which performed it.**

7.2.1 HYPAS Guidance

Carlie Zumwalt

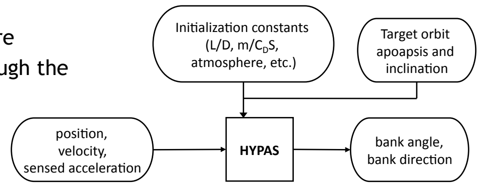
Aerocapture Overview



HYPAS Background and History

Background

- The Hybrid Predictor-corrector Aerocapture Scheme (HYPAS) targets a lifting vehicle through the atmosphere to the desired orbit apoapsis and inclination
- Bank modulation is used to control both drag and inclination angle



- HYPAS guidance is divided into longitudinal or "in-plane" control and lateral or "out-of-plane" control
  - The longitudinal control is divided into two phase: equilibrium glide phase and exit phase

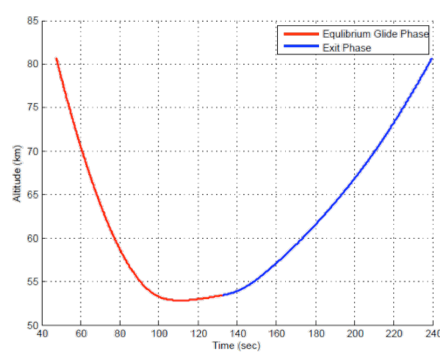
History of HYPAS

- HYPAS was originally developed by Chris Cerimele and Joe Gamble for the Aeroassist Flight Experiment (AFE) to be used for capture around Earth, before the program was cancelled.
- It has also been considered for use on missions such as the Mars Surveyor Program 2001, the CNES Mars 2005 Sample Return Orbiter, and the CNES Mars 2007 Premier Mission, prior to their cancellations
- HYPAS has been shown to be robust against a variety of L/D (Lift / Drag) , Ballistic Number (m/c_DS), atmospheres, entry conditions, and target orbits.

The HYPAS Guidance Algorithm

Longitudinal Control

Commands the vehicle to a specific bank angle magnitude, thus controls the amount of vertical in-plane lift.

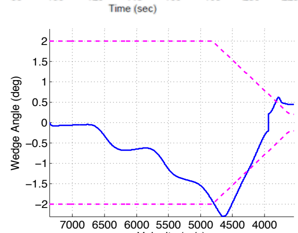


Equilibrium Glide
This phase was designed to allow for capture, and attempts to maintain an equilibrium glide condition, i.e. $\ddot{h} = 0$

Exit Phase
This phase was designed to target a specific exit state vector in order to accurately target orbit apoapse

Lateral Control

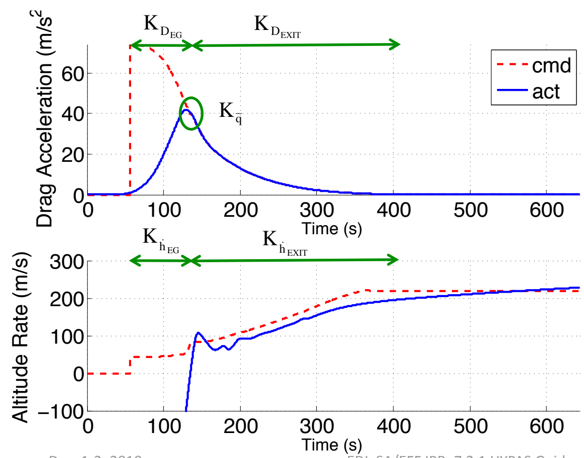
Commands the sign of the bank angle, which controls the direction of the out-of-plane lift, to maintain the desired orbit inclination to within a deadband, by performing roll reversals



The HYPAS Guidance Algorithm

HYPAS uses an analytically derived control algorithm based on drag deceleration and altitude rate error feedback to produce bank commands.

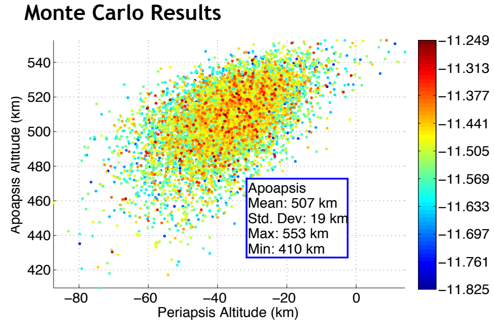
$$\left(\frac{L}{D}\right)\cos\phi_{cmd} = \frac{C_L}{C_D}\left[\cos\phi_{eq.gl.} - K_{\dot{h}}\left(\frac{\dot{h}-\dot{h}_{ref}}{\bar{q}}\right) + K_D\left(\frac{D-D_{ref}}{\bar{q}}\right)\right]$$

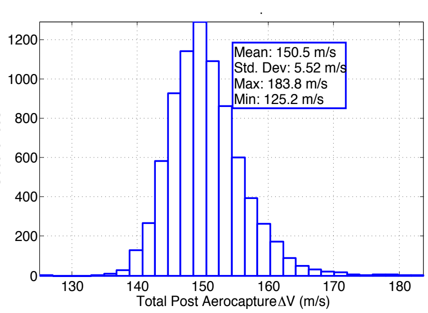


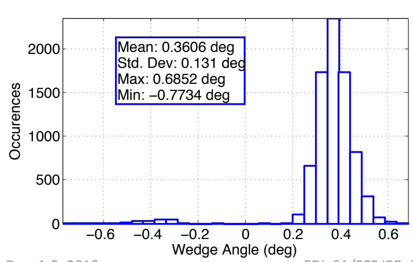
There are five gains used to tune HYPAS:
K_{DRAG} for Equilibrium Glide and Exit Phases,
K_{HDOT} for Equilibrium Glide and Exit Phases,
and K_{QBAR} to smooth out the profiles between the two phases.

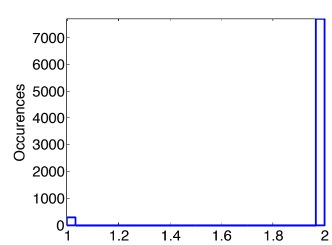
The HYPAS Guidance Algorithm

Monte Carlo Results









7.2.2 Shape Integral Aerocapture Guidance

David Way

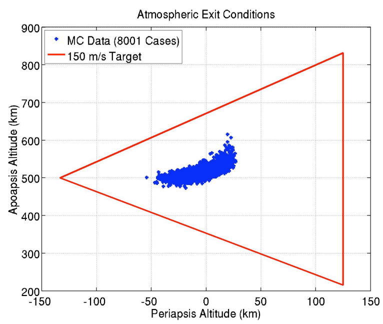
Outline

- **Performance Results**
- **Guidance Development**
  - **Equations of Motion**
  - **Shape Integral Definition**
  - **Reference Trajectory Approximation**
  - **Closed-loop Equations**
- **Reference Trajectory Design**
- **Lateral Guidance**

Shape Integral Performance

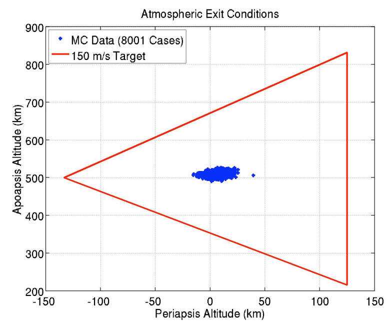
EDL-SA

6-DoF, L/D = 0.25, No Jettison



95% CI for $\Delta V_{99.87\%}$ = [145.1, 147.9] m/s

6-DoF, L/D = 0.25, With Jettison

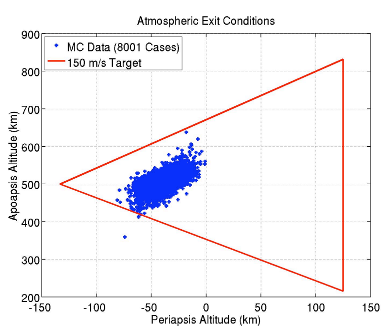


95% CI for $\Delta V_{99.87\%}$ = [140.0, 142.8] m/s

More Shape Integral Performance

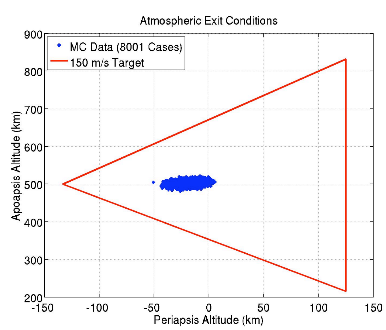
EDL-SA

6-DoF, L/D = 0.1, No Jettison



95% CI for $\Delta V_{99.87\%}$ = [203.3, 215.0] m/s

6-DoF, L/D = 0.1, With Jettison



95% CI for $\Delta V_{99.87\%}$ = [185.4, 190.7] m/s

Equations of Motion

EDL-SA

1. $\dot{V} + \frac{\mu}{r^2}\sin\gamma + \frac{q}{\beta} = 0$

2. $\ddot{r} + \frac{\mu}{r^2} + \frac{q}{\beta}\sin\gamma - L/D\frac{q}{\beta}\cos\gamma - \frac{V^2}{r}\cos^2\gamma = 0$

<u>Integrate:</u>

3. $V = -\int_0^{t_{go}} \frac{q}{\beta}dt - \int_0^{t_{go}} \frac{\mu}{r^2}\sin\gamma\, dt + V_0$

4. $r = -\int_0^{t_{go}}\int_0^{t_{go}} \frac{q}{\beta}\sin\gamma\, dt^2 - \int_0^{t_{go}}\int_0^{t_{go}} \frac{\mu}{r^2}dt^2 + \int_0^{t_{go}}\int_0^{t_{go}} L/D\frac{q}{\beta}\cos\gamma\, dt^2 + \int_0^{t_{go}}\int_0^{t_{go}} \frac{V^2\cos^2\gamma}{r}dt^2 + \dot{r}_0 t_{go} + r_0$

<u>Normalize Integrals:</u>

5. $\Delta V = t_{go}\left\{-\left(\frac{q_0}{\beta}\right)I_q - \left(\frac{\mu}{r_0^2}\right)I_\mu\right\}$

6. $\Delta r = t_{go}^2\left\{-\left(\frac{q_0}{\beta}\right)II_q - \left(\frac{\mu}{r_0^2}\right)II_\mu + \left(2\varphi L/D_{\max}\frac{q_0}{\beta}\right)II_{\Delta u} - \left(L/D_{\max}\frac{q_0}{\beta}\right)II_{LD} + \left(\frac{V_0^2}{r_0}\right)II_c\right\} + \dot{r}_0 t_{go}$

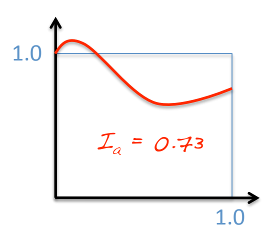
"Shape Integral" Definition

EDL-SA

$$\int_0^{t_{go}} a\, dt \quad = \quad t_{go}a_0\int_0^1\left(\frac{a}{a_0}\right)d\tau \quad = \quad t_{go}a_0 I_a$$

$$I_a \equiv \left[\frac{\int_0^{t_{go}} adt}{t_{go}a_0}\right]$$

- **Definite integrals, appearing in the equations of motion, are normalized by the time-to-go and current states**
- **These normalized integrals have been stripped of their magnitude and now contain only information related to the shape of the integrand (on a unit square)**
  - **hence the name "shape integral"**
- **Values for shape integrals may be computed in one of two ways:**
  1. **Analytically**
     - **Assume a particular shape function**
     - **Integrate analytically**
     - **Value provided on-board by a dedicated sub-routine**
  2. **Numerically**
     - **Optimize a reference trajectory**
     - **Integrate numerically**
     - **Value provided on-board by table interpolation**



- **Shape integrals are re-dimensionalized within the guidance to algebraically solve the original equations of motion**
  - **Exact solution (error is in the approximation of the shape integrals)**

Reference Trajectory Approximation

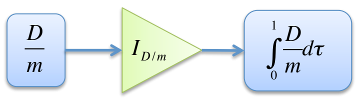
EDL-SA

1. $$\int_0^1 a^{traj} d\tau = a_0^{traj} I_a^{traj}$$

2. $$\int_0^1 a^{ref} d\tau = a_0^{ref} I_a^{ref}$$

3. $$I_a^{traj} \approx I_a^{ref}$$

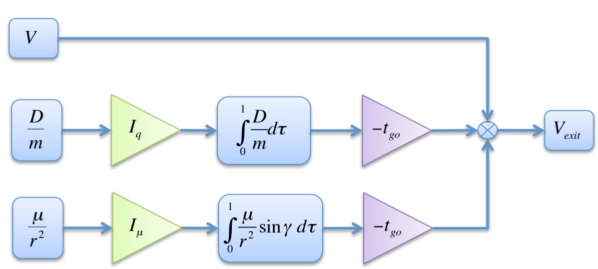
4. $$\int_0^1 a^{traj} d\tau \approx a_0^{traj} I_q^{ref} = \left(\frac{a_0^{traj}}{a_0^{ref}}\right) \int_0^1 a^{ref} d\tau$$

5. 

- **Eqns. 1 & 2 follow directly from the definition of the shape integral**
  1. **actual trajectory**
  2. **reference trajectory**
- **Eqn. 3 is the key assumption. The value of the shape integral for the actual trajectory is approximately the same as that for the reference trajectory.**
  - **The two trajectories have the <u>same shape</u>.**
- **Eqn. 4 shows that this assumption results in scaling the reference trajectory integral by the ratio of the current value of the normalization parameter**
  - **e.g. the ratio of the sensed accelerations**
- **Eqn. 5 shows the result. The shape integral (from the reference trajectory) is used as a gain on the current drag acceleration.**
  - **This gain converts the <u>current</u> sensed acceleration into an approximation of the <u>integrated acceleration</u> over the rest of the trajectory (to the terminal condition).**

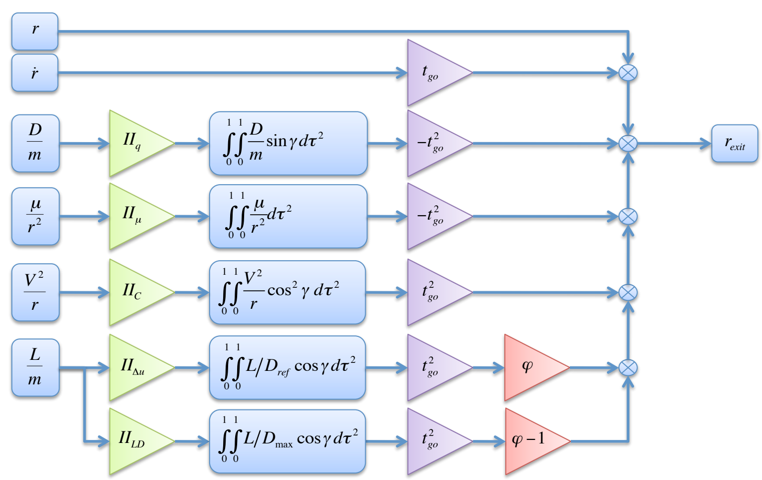
Velocity Equation (Block Diagram)

EDL-SA



Radius Equation (Block Diagram)

EDL-SA



Closed-Loop Guidance

EDL-SA

Reference tables

Parameters

Navigated state

1 $$t_{go} = \frac{\left(V_0 - V_{exit}\right)}{\left(\frac{q_0}{\beta}\right) I_q + \left(\frac{\mu}{r_0^2}\right) I_\mu}$$

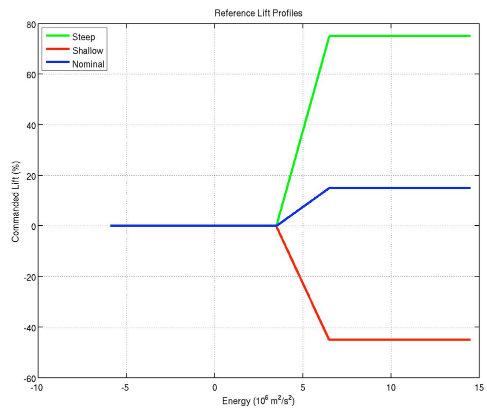
2 $$\varphi = \frac{\frac{\left(r_{exit} - r_0\right)}{t_{go}^2} - \frac{\dot{r}_0}{t_{go}} + \left(\frac{q_0}{\beta}\right) II_q + \left(\frac{\mu}{r_0^2}\right) II_\mu + \left(L/D_{\max}\frac{q_0}{\beta}\right) II_{LD} - \left(\frac{V_0^2}{r_0}\right) II_c}{\left(2L/D_{\max}\frac{q_0}{\beta}\right) II_{\Delta u}}$$

3 $$L/D_{cmd} = \varphi L/D_{ref} + \left(\varphi - 1\right) L/D_{\max}$$

```
// Required Navigation Quantities
double energy;
double altitude_rate;
double radius;
double velocity;
double filtered_drag_acceleration;
double gravitational_acceleration;
double centrifugal_acceleration;
```

Reference Trajectory Implementation

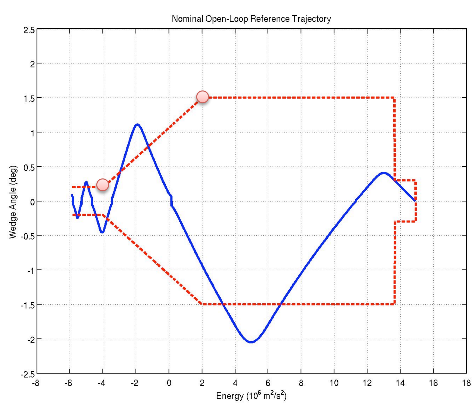
EDL-SA



- Three reference trajectories are used
  - Nominal
  - Steep
  - Shallow
- Each reference is optimized to target the desired apoapsis altitude
  - 3-DoF
  - Includes bank reversals
  - Drag and lift filters
  - Calculate integrals
- Tables of shape integrals and reference lift profile generated in Matlab
- flight-path-angle used to interpolate between references

Lateral Guidance Implementation

EDL-SA



- Bank reversals are commanded when wedge angle exceeds a parameterized dead-band
- Dead-band is implemented as a linear interpolation between two points, with no extrapolation
- First and Second Reversals are scheduled on energy
- First reversal direction direction tuned for either over-the-top or underneath.
- All subsequent reversals are tuned for underneath

Comments

EDL-SA

- Shape Integral Guidance is a viable alternative for aerocapture
  - Performance is very good
  - Results show the algorithm is robust to very large dispersions
  - Very few lines of code make it fast and easy to validate/debug
- Shape Integral may be used either with or without jettison
  - Jettison triggered on navigated apoapsis altitude
  - Performance improves with jettison
- General shape integral methodology may be used in other guidance problems
  - Other aerocapture control stategies
  - Gravity turn guidance
  - Entry guidance
  - Pin-point landing
  - etc

EDL-SA

Back-up

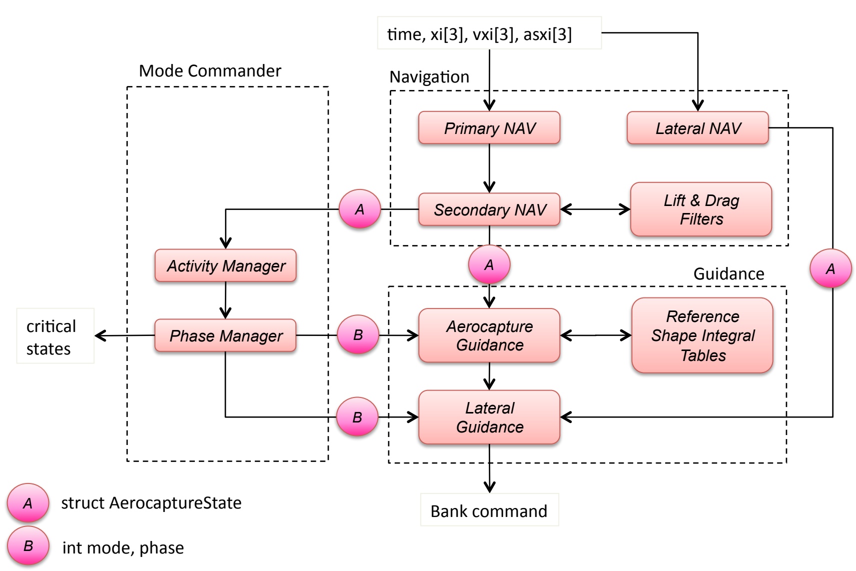
Source Code (In-Plane Guidance)

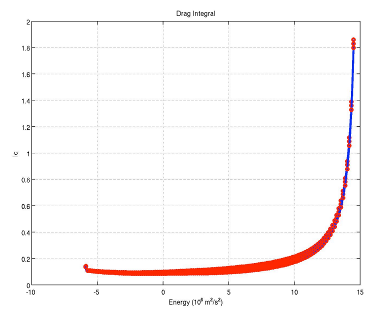
EDL-SA

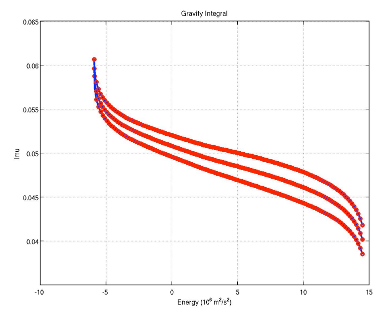
```c
static void closed_loop_aerocapture_guidance(AerocaptureState *state, AerocaptureGuidanceStruct *aerocap)
{
        /* Parameters */
        double LoD   = aerocap->lift_to_drag_ratio;
        double fract = aerocap->in_plane_lift_fraction;

        /* Shape Integrals (from reference tables) */
        double lref  = aerocap->reference_lift;
        double Iq    = aerocap->drag_integral;
        double Imu   = aerocap->gravitational_integral;
        double IIq   = aerocap->drag_double_integral;
        double IImu  = aerocap->gravitational_double_integral;
        double IIu   = aerocap->lift_increment_double_integral;
        double IIld  = aerocap->lift_down_double_integral;
        double IIC   = aerocap->centrifugal_double_integral;

        /* Navigated or Sensed State */
        double rdot  = state->altitude_rate;
        double dr    = state->delta_radius;
        double dV    = state->delta_velocity;
        double agrav = state->gravitational_acceleration;
        double acent = state->centrifugal_acceleration;
        double adrag = state->filtered_drag_acceleration;
        double alift = state->filtered_lift_acceleration;

        /* Solve for time-to-go & "throttle" */
        double tgo   = dV / ( adrag*Iq + agrav*Imu );
        double phi   =   ( dr/tgo/tgo - rdot/tgo + adrag*IIq + agrav*IImu + alift*IIld - acent*IIC )
                       / ( 2.0 * alift * IIu );

        /* outputs */
        aerocap->time_to_go = tgo;
        aerocap->lift_gain = phi;
        aerocap->commanded_lift_to_drag = phi * lref + (phi - 1.0) * LoD;

        /* limit commanded L/D */
        limit_double_minimum_maximum(&aerocap->commanded_lift_to_drag, -LoD*fract, LoD*fract);
        return;
}
```

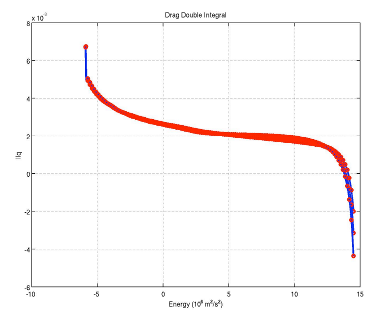

GN&C Block Diagram

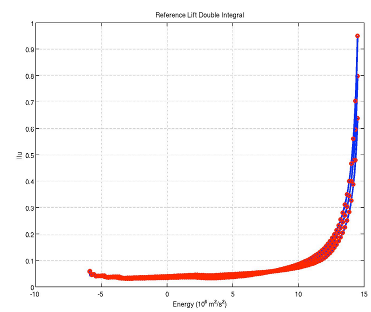
EDL-SA

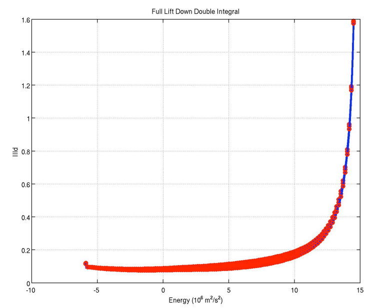


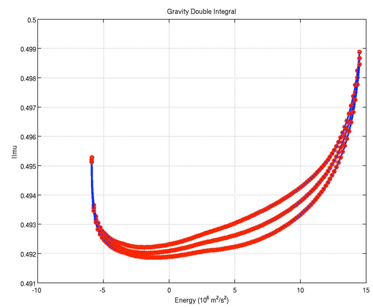

Drag Integral
Iq
Energy (10^6 m^2/s^2)

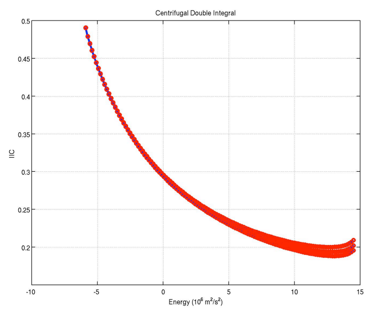

Gravity Integral
Imu
Energy (10^6 m^2/s^2)

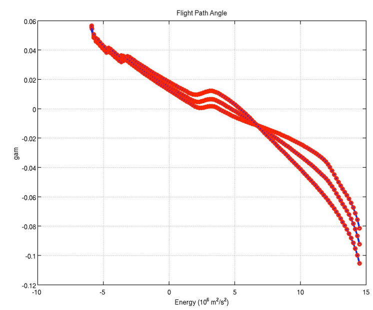

Drag Double Integral
x 10^{-3}
IIq
Energy (10^6 m^2/s^2)


Reference Lift Double Integral
IIu
Energy (10^6 m^2/s^2)

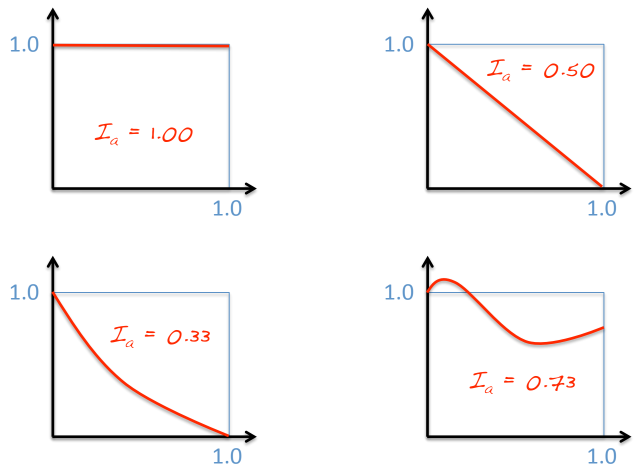

Full Lift Down Double Integral
IId
Energy (10^6 m^2/s^2)


Gravity Double Integral
IImu
Energy (10^6 m^2/s^2)


Centrifugal Double Integral
IIC
Energy (10^6 m^2/s^2)


Flight Path Angle
gam
Energy (10^6 m^2/s^2)

Examples



7.2.3 TPC Guidance

Eric Queen

Overview

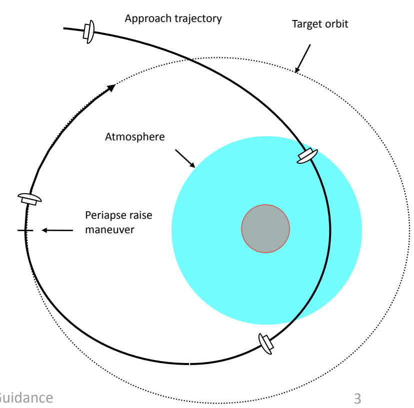
- TPC Algorithm overview
- Tuning Parameters
- Monte Carlo Results
  - L/D = 0.25 w/ Jettison
  - L/D = 0.10 w/ Jettison
  - L/D = 0.25 No Jettison
  - L/D = 0.10 No Jettison
  - An issue w/ Jettison
- Conclusions

The TPC Guidance Algorithm

EDL-SA

- Similar to terminal phase of Apollo Earth-return entry guidance
  - Based on Calculus-of-Variations approach
  - Boundary conditions changed to reflect different mission
- Uses reference trajectory to determine sensitivities of final condition to changes in control
  - Reference trajectory determined offline – not stored onboard
  - Guidance does not attempt to follow reference trajectory
- Bank reversals keep inclination (or wedge angle) error within desired limits.
  - Reversals triggered when inclination or wedge exceeds variable-width deadband

Aerocapture = single pass through atmosphere to slow from hyperbolic to elliptical orbit



TPC In-plane Control

EDL-SA

Bank angle Command:

$$\cos\phi_{cmd} = \cos\phi_{ref} + \frac{-\lambda_V (V - V_{ref}) - \frac{\lambda_\gamma}{V\cos\gamma}\left(\dot{h} - \dot{h}_{ref}\right) + \frac{m h_s \lambda_h}{D}\left(\frac{D}{m} - \frac{D_{ref}}{m}\right)}{\lambda_\phi}$$

where ϕ is the bank angle, V is velocity, γ is the flight path angle, h is the altitude, D is the drag force, h_s is the atmospheric scale height, m is the vehicle mass, α is the angle of attack and λ_V, $\lambda\gamma$, and λ_h are the costates for velocity, flight path angle and altitude.

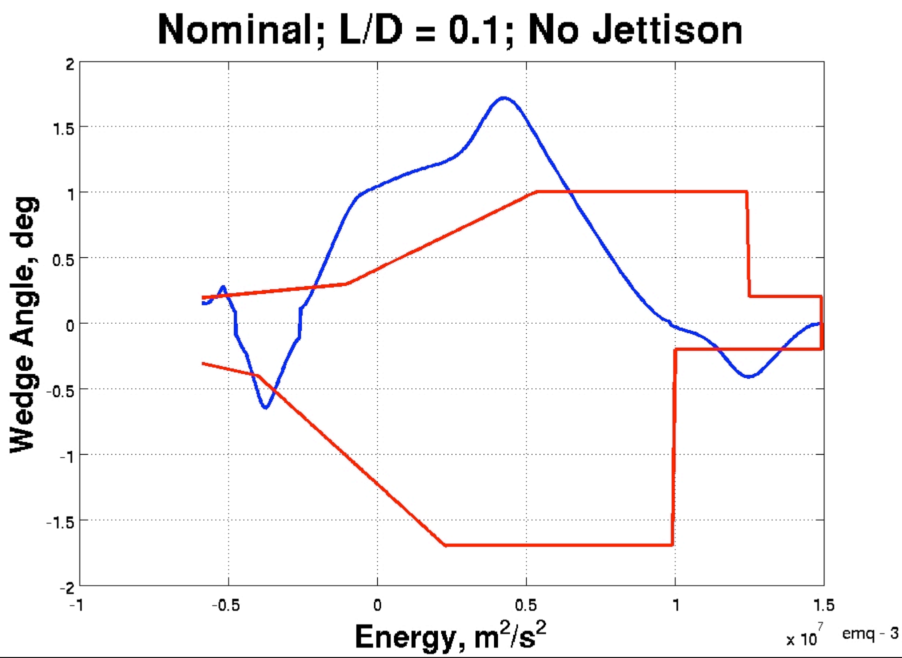
λ_u is sometimes refered to as the "control costate", defined as:

$$\lambda_u = \int_{t_0}^{t_f} \left(\frac{\partial f}{\partial u}^T \lambda \right) dt$$

With u representing cosine of the bank angle.

TPC Lateral Control

EDL-SA



Primary Tuning Parameters

EDL-SA

Parameter	Value
Reference Lift Profile	Linear w/ E: 110-135 deg
Drag Accel overcontrol gain	5.0
Radius Rate overcontrol gain	8.0
Velocity overcontrol gain	0.0
Lift up/down standoff	15 deg
Reversal Direction E trigger	5.9e6
High E Bank under/over limit	120 deg
Low E Bank under/over limit	60 deg
Density Estimator altitude pass	380 m
Density Estimator # samples	180
Density Estimator rho_0	0.05 kg/m^3
Density Estimator scaleheight	7.657 km
Density Estimator initial alt steps	50 m

L/D = 0.25, w/ Jettison, Propagated Nav

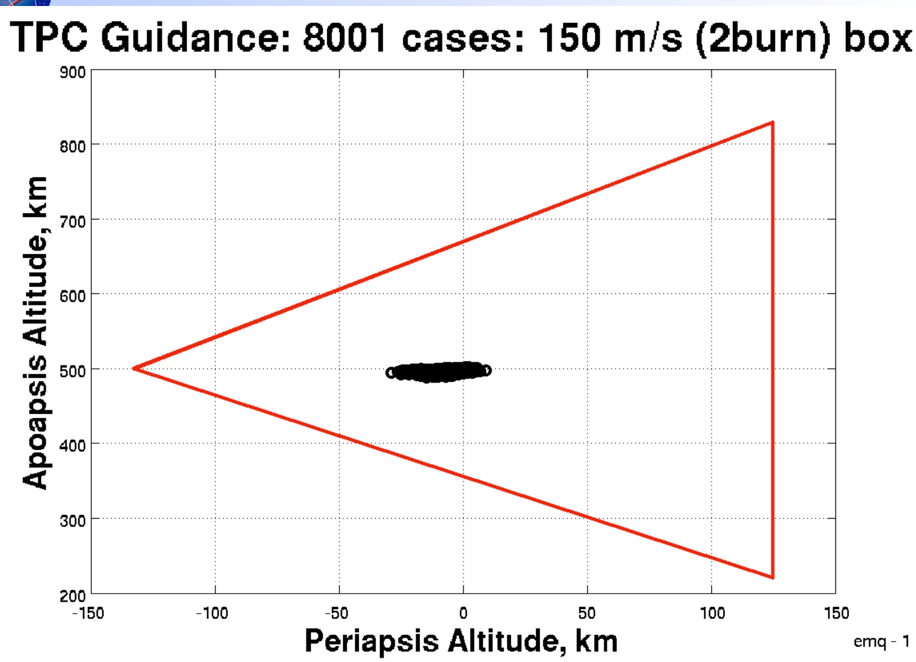
Mean + 3 σ Δ V = 141.80

99.87% Δ V = 142.77

Mean EFPA = -11.8345

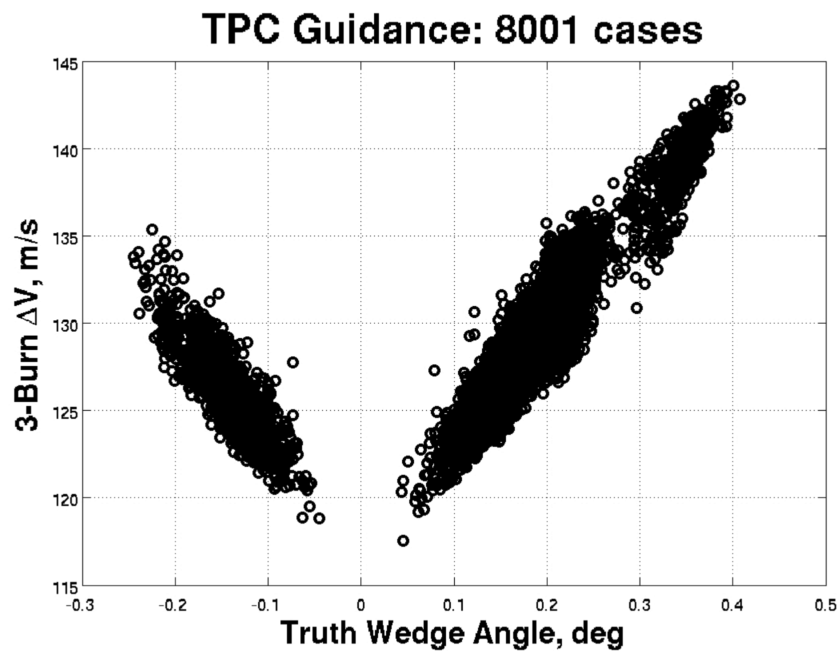
L/D = 0.25 w/ Jettison

EDL-SA



L/D = 0.25 w/ Jettison

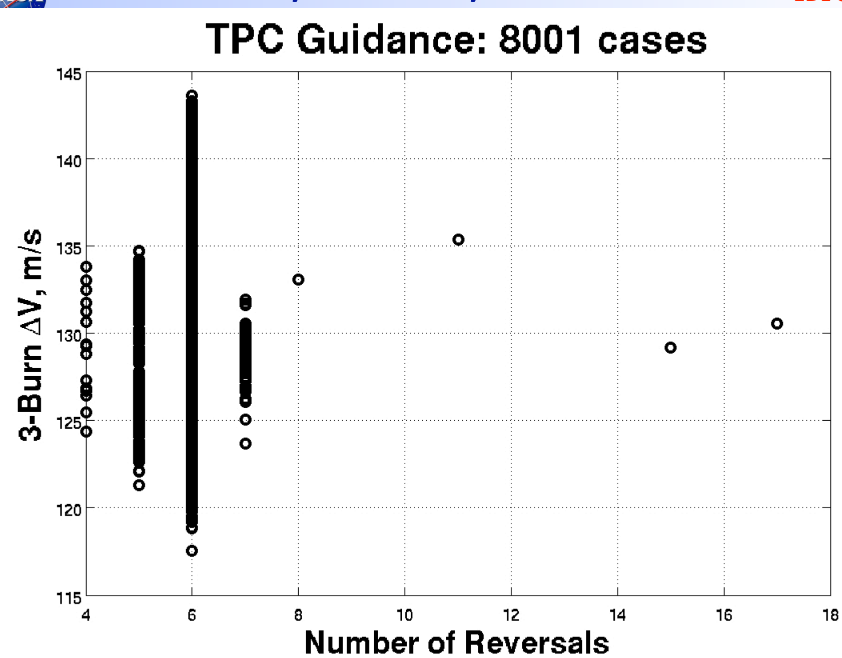
EDL-SA



emq - 2

L/D = 0.25 w/ Jettison

EDL-SA



emq - 3

L/D = 0.1, w/ Jettison, Propagated Nav

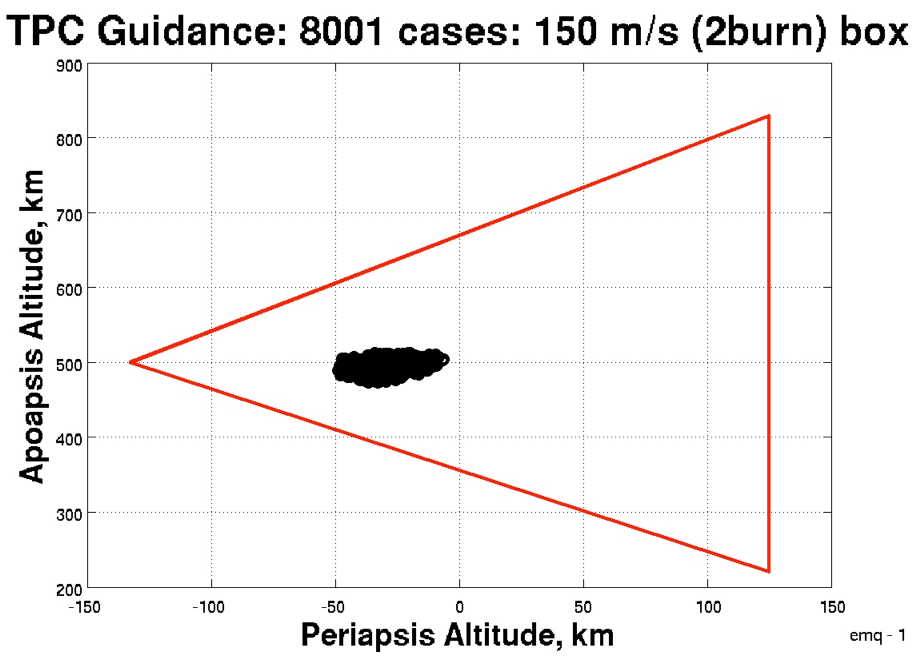
Mean + 3 σ Δ V = 145.15

99.87% Δ V = 148.03

Mean EFPA = -11.7700

L/D = 0.10 w/ Jettison

EDL-SA



EDL-SA

L/D = 0.25, No Jettison, Propagated Nav

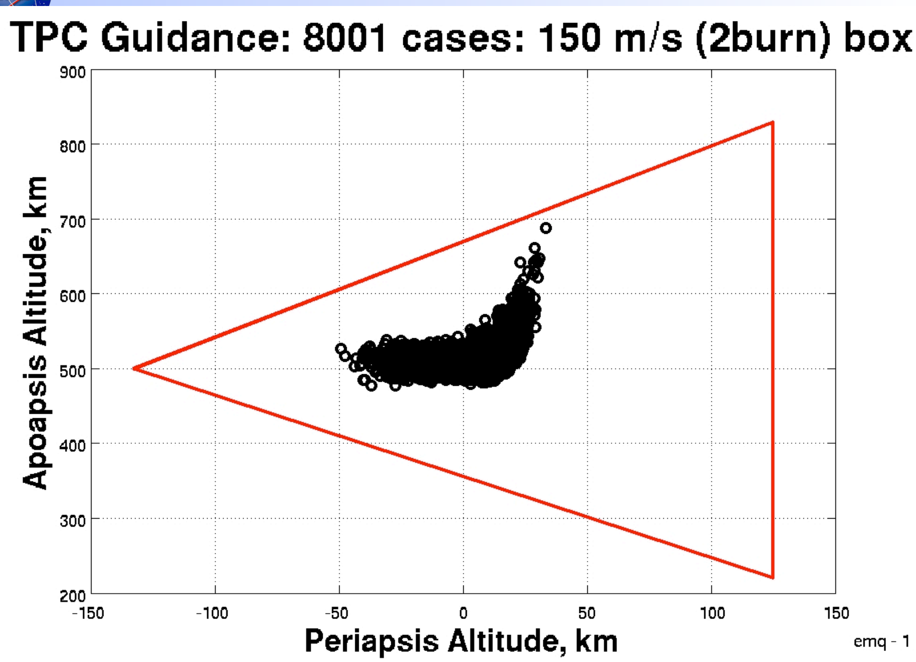
Mean + 3 σ Δ V = 142.96

99.87% Δ V = 148.73

Mean EFPA = -11.9900

L/D = 0.25 No Jettison

EDL-SA



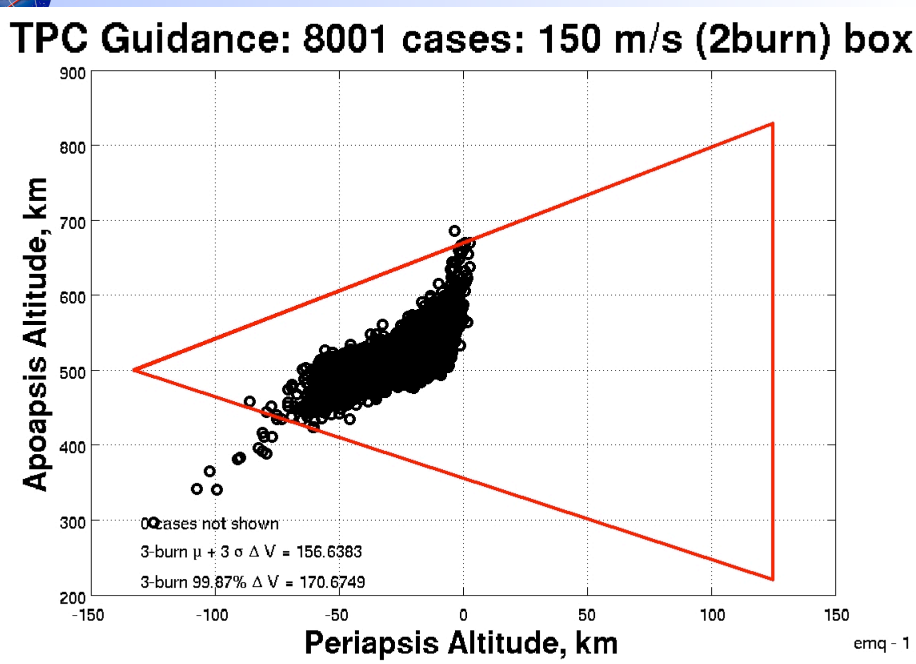
L/D = 0.10, No Jettison, Propagated Nav

Mean + 3 σ Δ V = 142.96

99.87% Δ V = 148.73

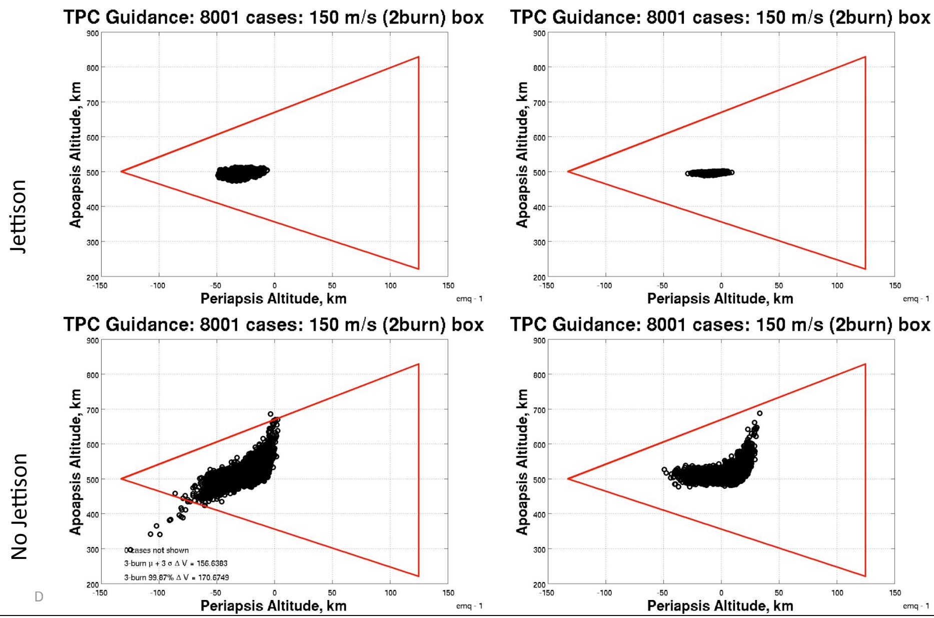
Mean EFPA = -11.5383

L/D = 0.10 No Jettison



L/D = 0.1 L/D = 0.25

EDL-SA



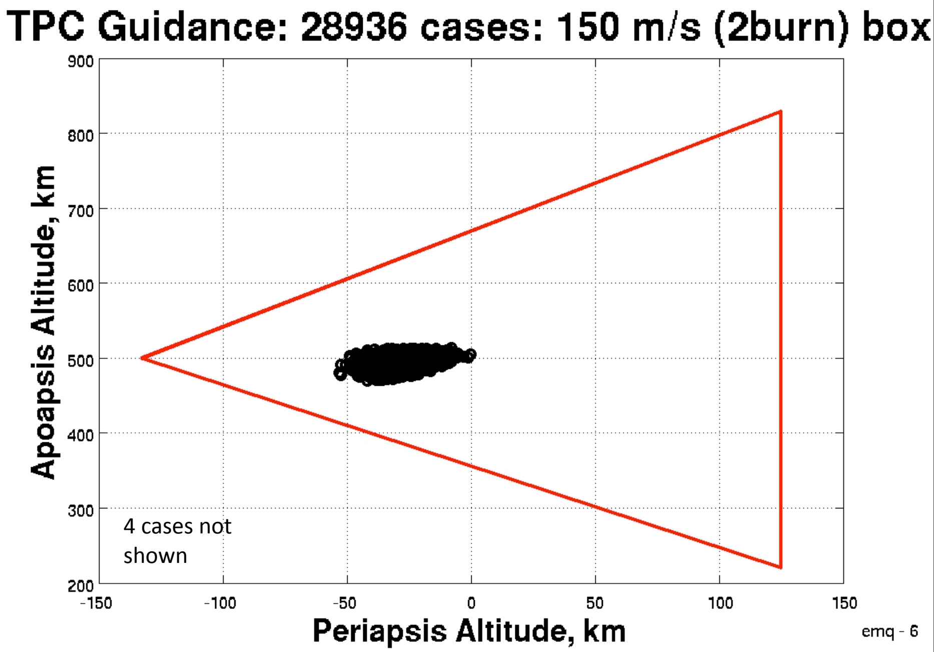
Jettison Trajectories

EDL-SA

- Trajectories w/ aeroshell jettison are tuned to low apoapsis
- Dispersions lead to some few cases with high apoapsis
  - These cases saturate at lift-down control
  - “boomerang-shaped” peri-apoapsis footprint
- In very rare cases, full lift-down will not sufficiently lower apoapsis
  - These cases cannot be corrected by aeroshell jettison
- Final apoapsis can be very sensitive to small changes after control saturates
  - There is a “cliff” with no warning of very bad performance

L/D = 0.10 w/ Jettison

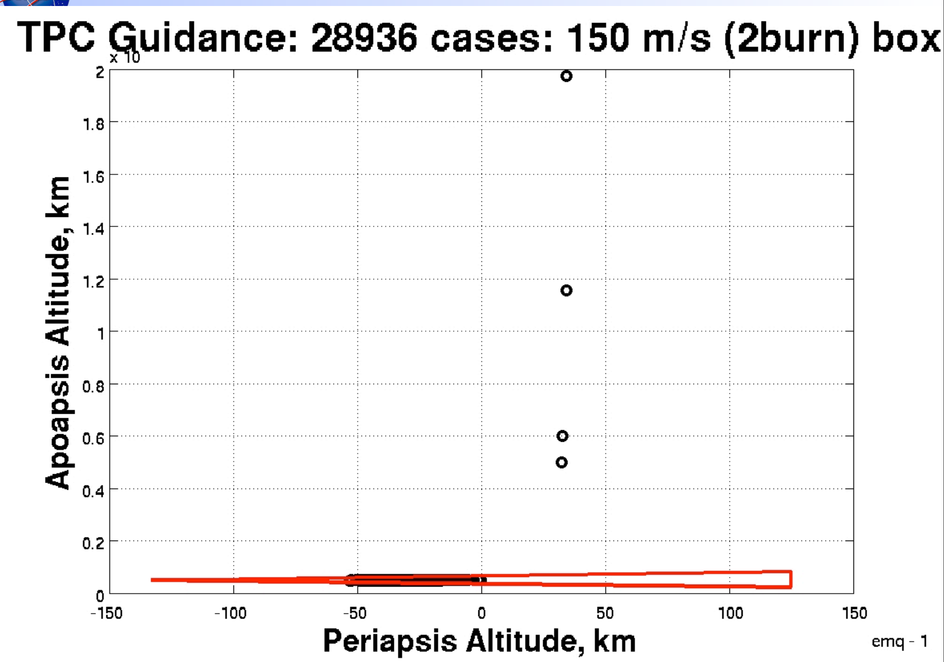
EDL-SA



emq - 6

L/D = 0.10 w/ Jettison

EDL-SA



emq - 1

EDL-SA

Conclusions

- TPC Guidance can fly all 4 missions considered here.
  - Most effective tuning parameter is reference trajectory
- L/D = 0.25 performs well with or without jettison
- L/D = 0.10 with jettison performs well
- L/D = 0.10 without jettison is a challenge for the given dispersions, ΔV budget
- Aeroshell jettison has a very large impact on performance
  - May mask a “cliff” in performance

EDL-SA

Backup

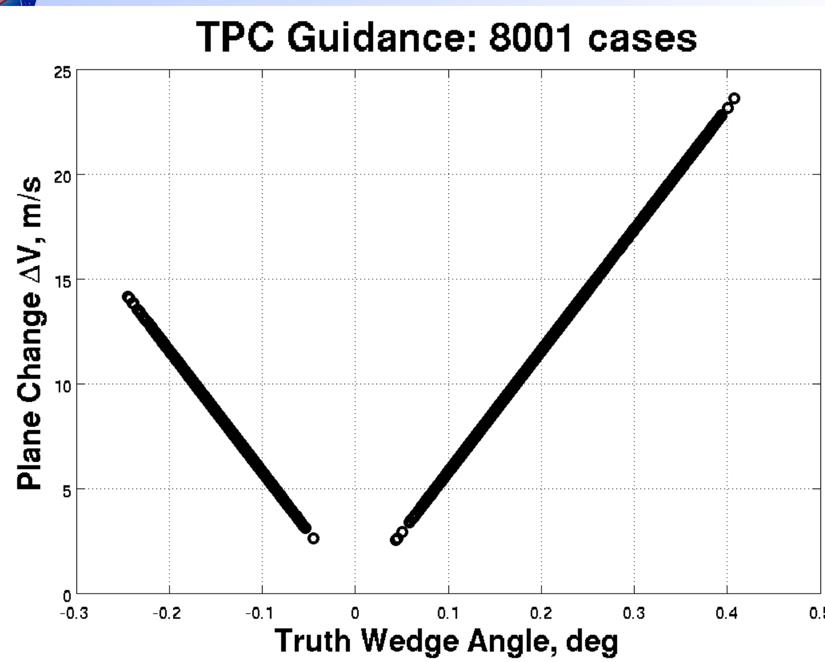
History of TPC

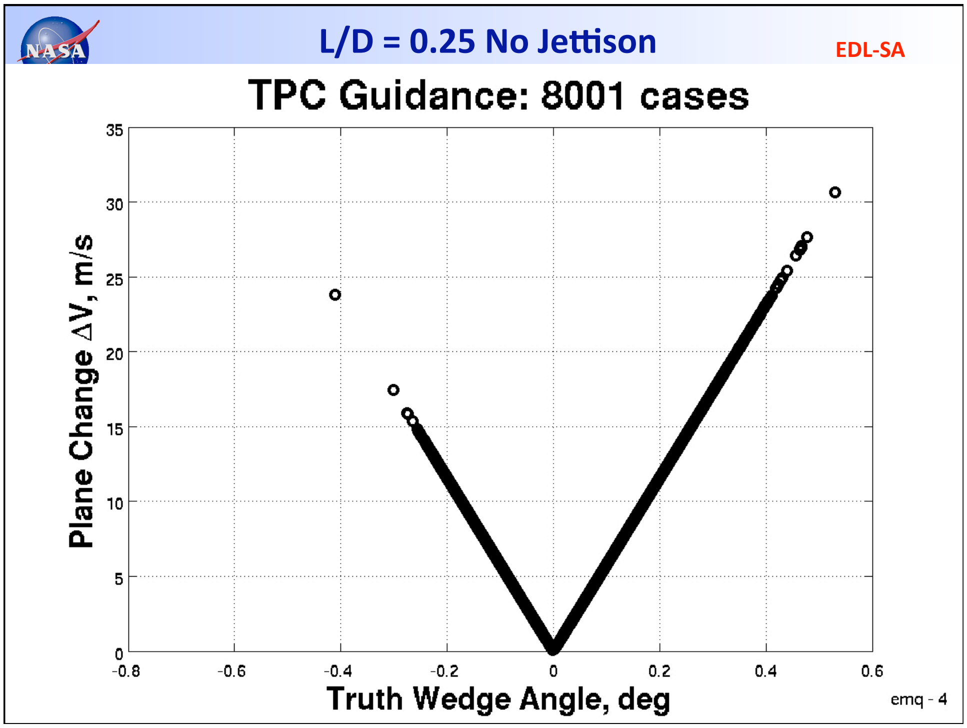
EDL-SA

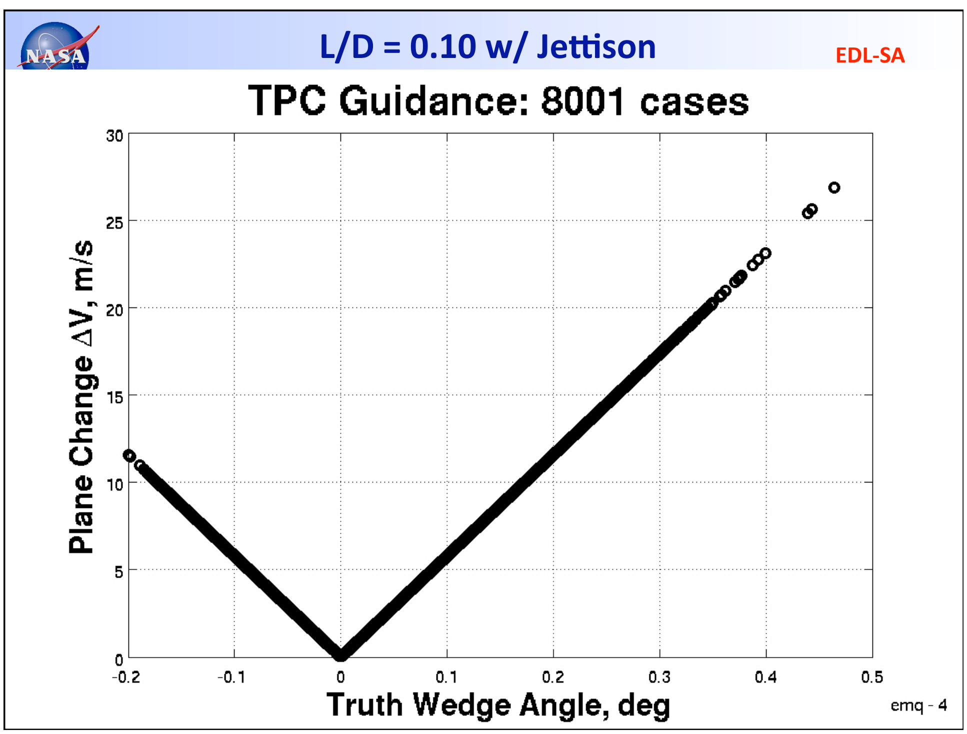
- Bank-modulated controller originally developed for Mars Surveyor Program 2001 (MSP ’01)
  - Apollo-style guidance under consideration for lander at that time
  - “Related” aerocapture guidance desired for compatibility
  - Aerocapture was later eliminated from the mission plan.
- Considered for the CNES Mars 2005 Sample Return Orbiter, and later, the CNES Mars 2007 Premier Mission. Aerocapture was later eliminated from the mission plan.

L/D = 0.25 w/ Jettison

EDL-SA

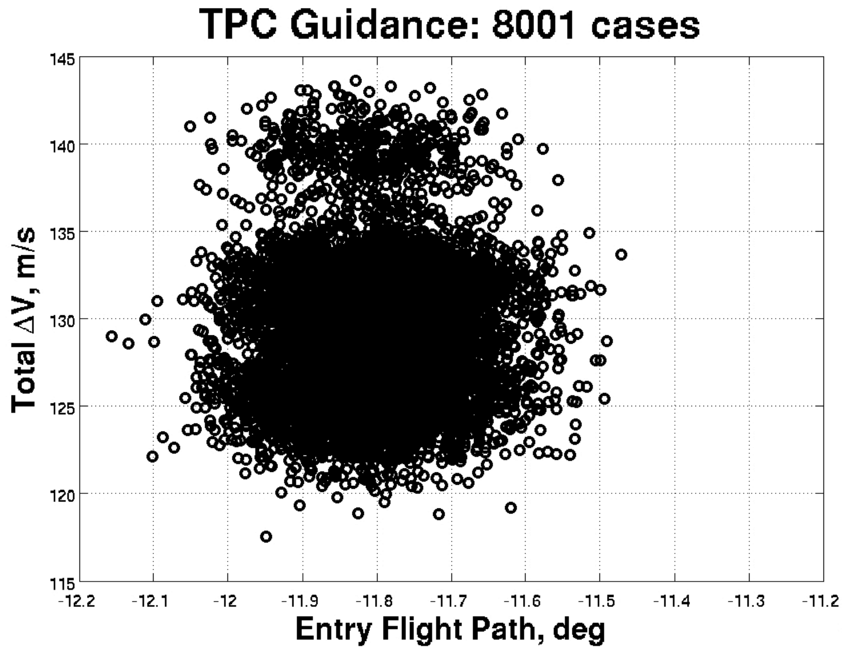



NASA
L/D = 0.25 No Jettison
EDL-SA
TPC Guidance: 8001 cases
Plane Change ΔV, m/s
Truth Wedge Angle, deg
0
5
10
15
20
25
30
35
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
emq - 4


NASA
L/D = 0.10 w/ Jettison
EDL-SA
TPC Guidance: 8001 cases
Plane Change ΔV, m/s
Truth Wedge Angle, deg
0
5
10
15
20
25
30
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
emq - 4

L/D = 0.25 w/ Jettison

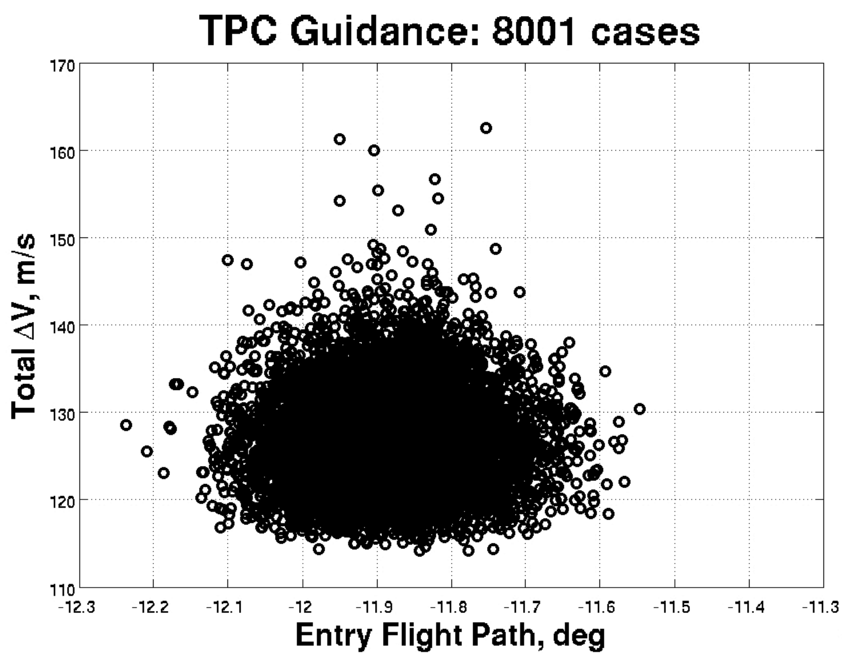
EDL-SA



emq - 5

L/D = 0.25 No Jettison

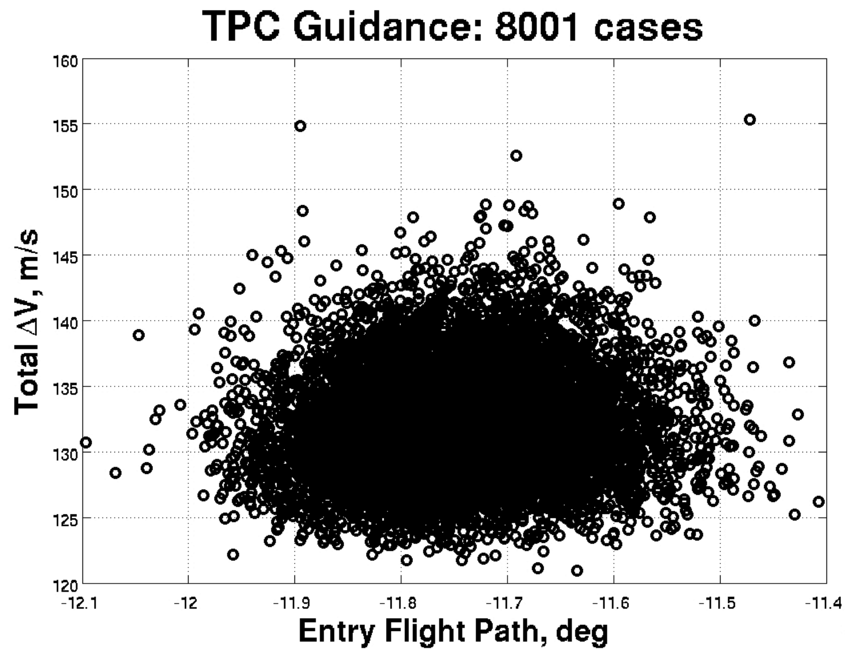
EDL-SA



emq - 5

L/D = 0.10 w/ Jettison

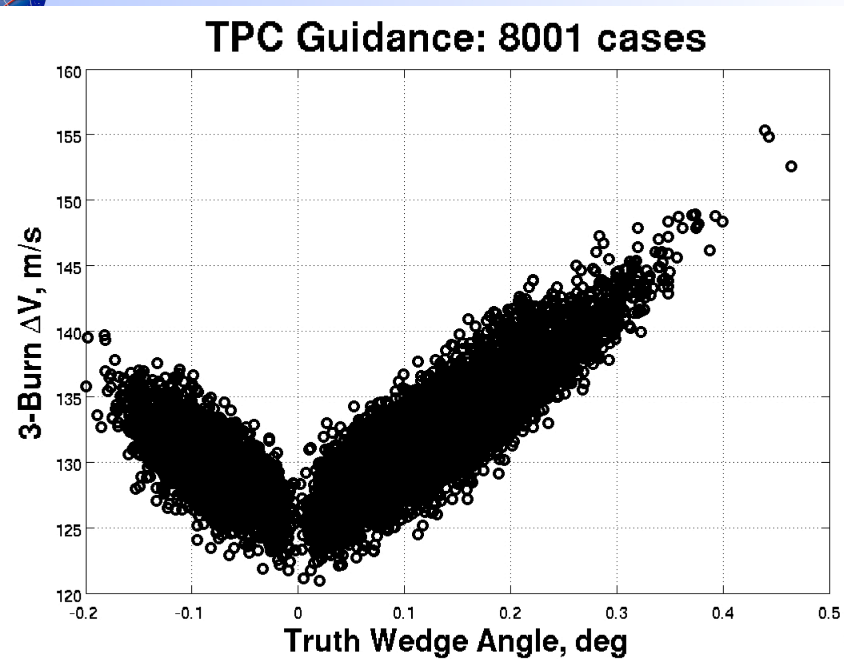
EDL-SA



emq - 5

L/D = 0.10 w/ Jettison

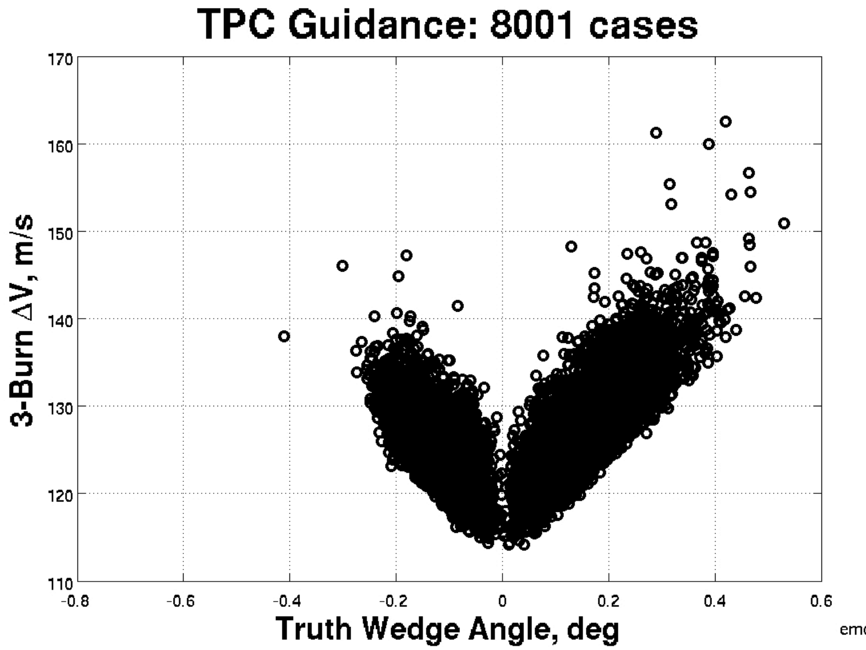
EDL-SA



emq - 2

L/D = 0.25 No Jettison

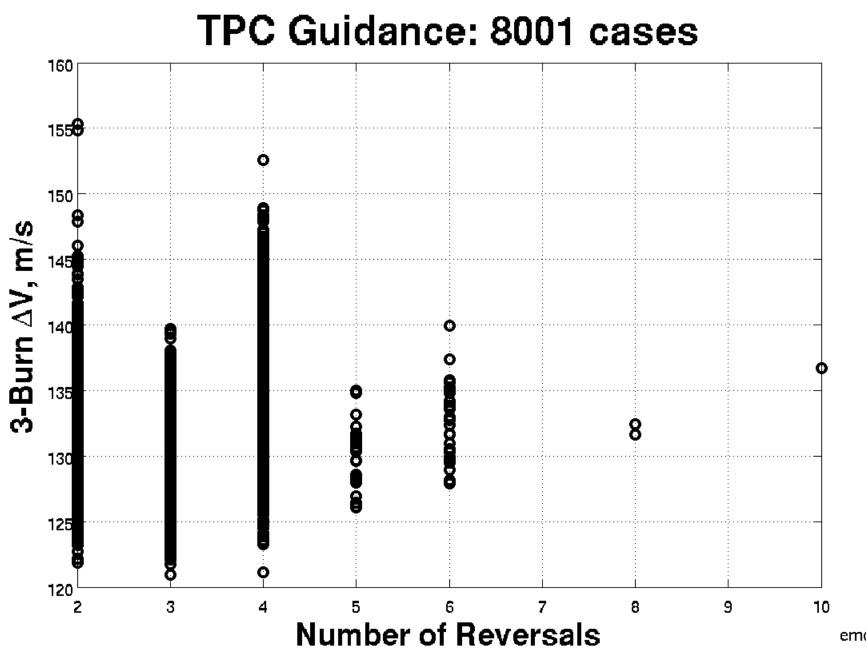
EDL-SA



emq - 2

L/D = 0.10 w/ Jettison

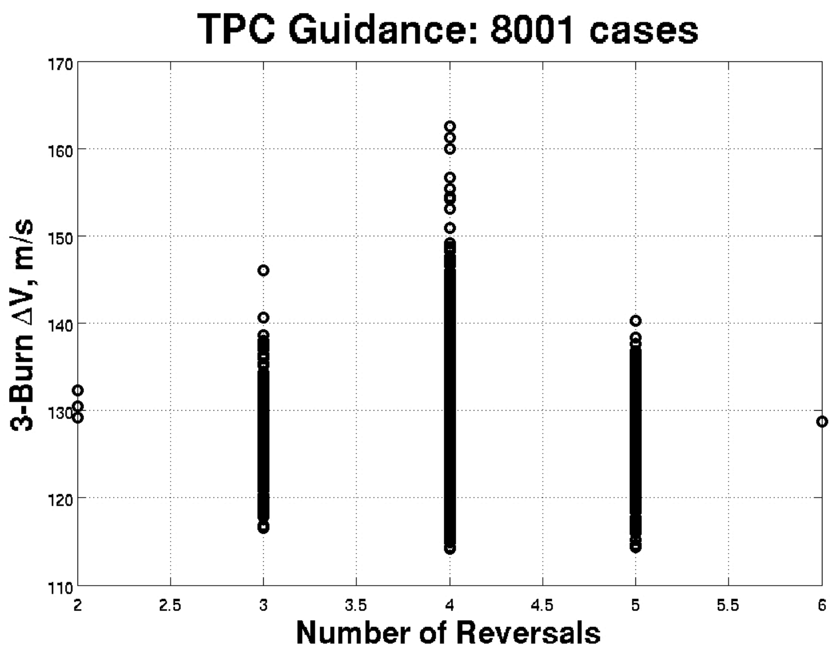
EDL-SA



emq - 3

L/D = 0.25 No Jettison

EDL-SA



emq - 3

7.2.4 Numerical Predictor Corrector (NPC) Aerocapture Guidance Algorithm

Dick Powell

Background

- Originally developed to support the Mars 2001 Lander and Aerocapture Orbiter Guidance Algorithm Downselect
- Evaluated for the 2005 CNES-led MSR Aerocapture Orbiter
- Modified to be included in EDLSA Simulation
- NPC integrates simplified equations of motion and iterates to determine control parameter required to meet constraint
  - Phase 1 – Update atmospheric and aerodynamic models only– inner loop guidance not triggered
  - Phase 2 – Guidance start (g trigger) to periapsis
    - Constraint – exit apoapsis
    - Control – bank angle command (note: exit phase bank angle remains constant)
  - Phase 3 – Periapsis to atmospheric exit
    - Constraint – exit apoapsis
    - Control – bank angle command
  - Phase 4 – Jettison control phase (if active)
    - At specified instantaneous apoapsis – fly lift down (maximizes exit periapsis)
    - Determine time to jettison such that desired exit apoapsis is achieved

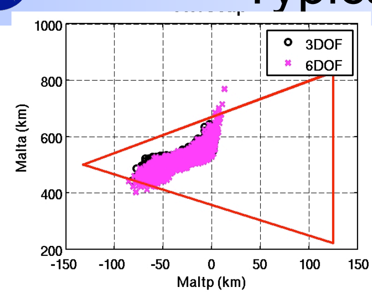
Background - Cont.

EDL-SA

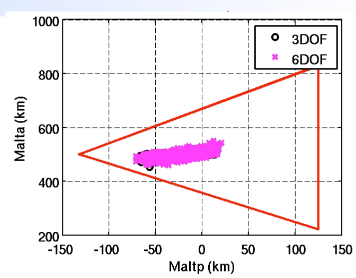
- Phases have 1 control and 1 constraint (minimizes potential of singularities)
- Pseudo controller used for bank channel dynamics when bank angle guidance is active (acceleration and rates)
- Trim routine used for alpha (bank angle guidance and cg control) and beta (cg control)
- Outer loop of guidance updates internal atmospheric density and aerodynamics
- Inner loop (called every 10 sec) determines guidance command parameter – passes bank angle magnitude and bank reversal times to control system

Typical Results

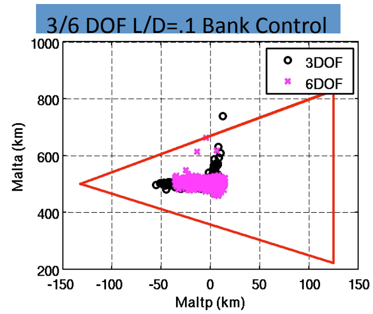
EDL-SA



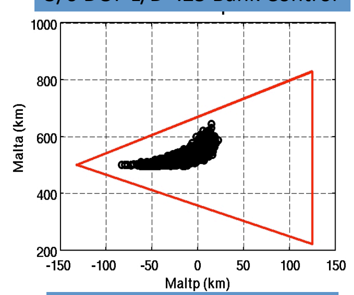
3/6 DOF L/D=.1 Bank Control



3/6 DOF L/D=.25 Bank Control



3/6 DOF L/D=.1 Bank Control with Jettison



3 DOF L/D =0.25 CG Control

Summary

EDL-SA

- NPC Aerocapture successfully incorporated in EDL-SA simulation
- NPC demonstrated for L/D trades (3/6 DOF) and 3 DOF cg study

7.3 Lessons Learned/Future Work

Dick Powell

Summary of Simulation

- Single simulation (source/input/Monte Carlo) containing all options worked
- Simulation jointly developed by LaRC/ JSC that incorporates:
  - 3/6 DOF
  - Aerocapture and EDL
  - ALHAT sensors
  - 2 IMU models
  - Multiple guidance algorithms
  - Multiple control algorithms
- Input deck developed that allows all reasonable combinations within same deck
- Same Monte Carlo inputs used for all simulations
- Simulation under source control
- NESC sponsored mods (Nav Filter, Pseudo Controller) used for this study

HIAD Controllability Lessons Learned

EDL-SA

- Bank angle control adequate for L/D = 0.25 for cases examined (incomplete – not all "difficult" cases examined)
- Bank angle control marginal (many cases saturated) for L/D = 0.1
- Jettisoning the HIAD under guidance control shows promising results to augment the low L/D
    - Requires large ballistic number mismatch (~≥10)
    - Requires that trajectory must be targeted deeper into the atmosphere such that the cases that would exit high without jettisoning will now exit no lower than desired apoapsis – increasing heat rate
    - Hides fact that many cases are saturated during guidance phase
    - Potential for "cliff" phenomena
- CG control demonstrated with 3 DOF – adding the dynamics of 6 DOF with only cg control and roll RCS has proven difficult

Future Work

EDL-SA

- **Complete the desired controllable matrix for bank angle control**
- **Rethink the cg controller**
- **Incorporate the "moving mass" dynamics to examine cg control**
- **Incorporate the dynamics of the flexure at the juncture of the rigid heat shield and the flexible structure (IRVE 4 analysis show this is potentially destabilizing)**
- **Consider other control strategies (e.g. shape control)**
- **Continue examination of jettisoning the HIAD under guidance control within the atmosphere**

EDL-SA

8.0 EDL-SA Exploration Feed Forward Conclusion

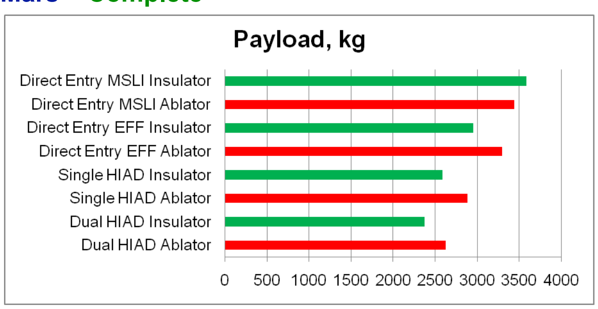
Alicia Cianciolo

EDL-SA

Evaluation Criteria

Promised EFF Results

1. Determine the maximum payload the Delta IV-H can deliver to 0 km MOLA at Mars – Complete



2. Determine the required performance of supersonic retro-propulsion system – Complete **Will will provide thrust coefficients**

RS-72 Pump Fed NTO/MMH throttleable engines, Isp = 338 s,

area ratio = 300,

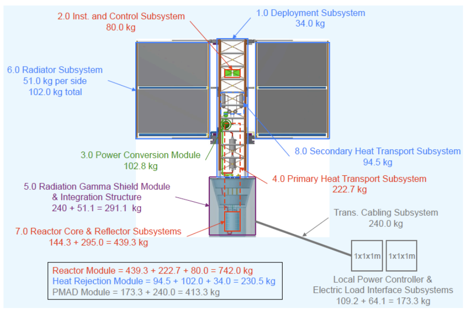
1.4 > Mach at SRP initiation > 1.8

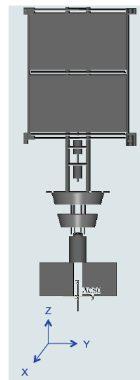
3 km >Altitude at SRP initiation > 8 km

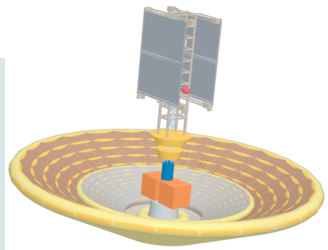
Evaluation Criteria
Promised EFF Results

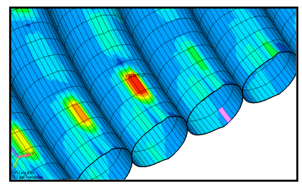
EDL-SA

3. **Perform the next level of detail on packaging, mass properties, transitions, structures, propulsion, etc**









Evaluation Criteria
Promised EFF Results

EDL-SA

4. **Determine optimum material/TPS, L/D, and size of the HIAD for aerocapture and entry – Complete**

		Dual HIAD		Single HIAD		Direct Entry, 7.2 km/s		Direct Entry, 5.8 km/s	
	Units	Ablator	Insulator	Ablator	Insulator	Ablator	Insulator	Ablator	Insulator
Payload	kg	2627	2371	2881	2589	3294	2953	3442	3584
Diameter	m	8	14	8	14	8	16	8	8

HIAD Controllability examined L/D from 0.1 to 0.25.

5. **Determine if active cg control provides benefits over the use of bank only – Incomplete**

Evaluation Criteria
Promised EFF Results

EDL-SA

6. **Determine the sensor performance ranges for an ALHAT like navigation & sensor system at Mars**

TRN

Expected states and ranges

- Altitude: 2 – 7 km
- Velocity: Mach 0.5 – 1.7

HDA:

Current trajectory nominal HDA flight condition

- Altitude = 1 km
- Look angle = -14 deg
- Path angle = 66 deg

Altimeter

- Activated at 6 km

Velocimeter

- Activated at 2 km and 150 m/s

EFF Technology Recommendations

EDL-SA

- Continue evaluation of ALHAT sensors adapted to Mars
- Continue development supersonic retropropulsion
- Include rigid body precursor configuration
- Continue to mature HIADS
- Include rigid deployables in design space
- Perform detailed evaluation of transitions
- Invest in advancements in flight instrumentation

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14. ABSTRACT
NASA senior management commissioned the Entry, Descent and Landing Systems Analysis (EDL-SA) Study in 2008 to identify and roadmap the Entry, Descent and Landing (EDL) technology investments that the agency needed to successfully land large payloads at Mars for both robotic and human-scale missions. Year 1 of the study focused on technologies required for Exploration-class missions to land payloads of 10 to 50 mt. Inflatable decelerators, rigid aeroshell and supersonic retro-propulsion emerged as the top candidate technologies. In Year 2 of the study, low TRL technologies identified in Year 1, inflatables aeroshells and supersonic retropropulsion, were combined to create a demonstration precursor robotic mission. This part of the EDL-SA Year 2 effort, called Exploration Feed Forward (EFF), took much of the systems analysis simulation and component model development from Year 1 to the next level of detail.

15. SUBJECT TERMS
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